United States
Department of
Agriculture

Forest Service

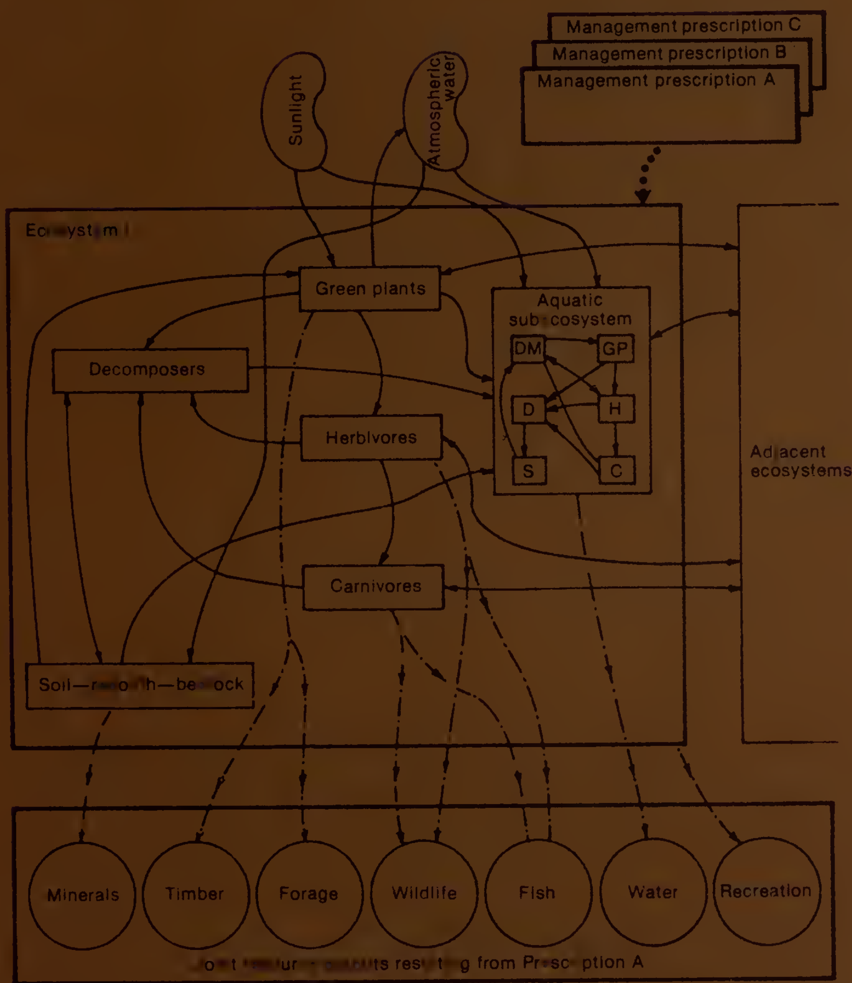
Rocky Mountain
Forest and Range
Experiment Station

Fort Collins,
Colorado 80526

General Technical
Report RM-106

Aggregate Timber Supply Analysis

Ralph J. Alig, Bernard J. Lewis, and Paul A. Morris



Abstract

Timber supply analysis techniques for broad geographical levels are summarized by land allocation, timber growth and yield, short-term harvest flows, and long-term timber investment modeling components. Representative techniques of these major analytical components are summarized in tabular form for supply regions. Aspects of aggregation and uncertainty in timber supply analyses are also discussed.

Acknowledgments

The authors extend special thanks for their help and advice to Darius M. Adams, Professor, Oregon State University; Richard L. Barber, Assistant Professor, Humboldt State University; J. Douglas Brodie, Associate Professor, Oregon State University; Daniel E. Chappelle, Professor, Michigan State University; Gary E. Dixon, Research Forester, USDA Forest Service Rocky Mountain Forest and Range Experiment Station; Alan R. Ek, Professor, University of Minnesota; Buddy Green, Forestry Aide, USDA Forest Service Rocky Mountain Forest and Range Experiment Station; William B. Kurtz, Associate Professor, University of Missouri—Columbia; Albert R. Stage, Principal Mensurationist, USDA Forest Service Intermountain Forest and Range Experiment Station, Moscow, Idaho; and several graduate students at the University of Minnesota and Oregon State University.

ERRATA SHEET

for

USDA Forest Service General Technical Report RM-106

Aggregate Timber Supply Analysis

Ralph J. Alig, Bernard J. Lewis and Paul A. Morris

The captions for Figures 2 (page 15) and 3 (page 20) should be reversed.

USDA Forest Service
General Technical Report RM-106

February 1984

Aggregate Timber Supply Analysis

Ralph J. Alig, Research Forester
Rocky Mountain Forest and Range Experiment Station[1]
Bernard J. Lewis, Research Fellow
College of Forestry, University of Minnesota
and
Paul A. Morris, Forestry Technician
Rocky Mountain Forest and Range Experiment Station[1]

[1] *Headquarters is in Fort Collins, in cooperation with Colorado State University.*

CONTENTS

Aggregate Timber Supply Analysis

Ralph J. Alig, Bernard J. Lewis, and Paul A. Morris

INTRODUCTION

Aggregate timber supply analyses examine long-run trends in stumpage supply and identify opportunities for influencing the course of those trends through management of the forest resource. These analyses support the formulation and direction of public and private timber policies. In this report, aggregate timber supply analysis refers to techniques for analyzing timber resource supplies for geographic areas ranging from substate to national levels.

This paper presents a broad overview of major analytical techniques for aggregate timber supply analysis, and is intended as a reference document for analysts of natural resource supplies. It provides brief descriptions of major techniques and their applications, and includes critiques from those who have designed, used, or examined these techniques. Bibliographical references refer the reader to specific documents containing detailed operational information (i.e., computational structure, operating costs, etc.) for the cited analytical techniques.

Analyses of timber supply have been approached from a variety of perspectives; the objectives of a particular timber supply study and data availability dictate the specific analytical techniques employed. As a starting point, one might consider the physical quantity or "supply" of timber in a particular geographic region. At a given point in time a certain amount of wood fiber is present, and the growth and mortality within this timber base may be modeled and projected under different management assumptions and for a variety of future time periods.

The "physical supply" of timber is governed by both physical and biological factors that affect timber growth and mortality, while the broader concept of economic timber supply is based on economic feasibility of growing and harvesting timber. Economic timber supply is a schedule of the quantities of stumpage at different prices that producers are willing to offer for sale in a specific market area in a given time period under the existing institutional framework.[2] This definition of timber supply is adopted for use in this report. It is not synonymous with that for "physical supply," because it incorporates the notion of responses to different timber prices based on opportunity costs related to the management and availability of standing timber. As an example of this distinction, degrees of timber accessibility are more fully reflected by economic supply than "physical supply" estimates.

An additional influence on timber supply is the form of institutional and/or administrative constraints which reduce the amount of timber from that which would otherwise be available from an economic standpoint. Parks and other areas withdrawn from the economically available timber base are a familiar example of institutional restrictions influencing timber supply. From an administrative perspective, constraints on timber production may take the form of targets for other forest outputs—wildlife, water, etc.—which must be achieved concurrently with the production of timber, thus reducing the economic timber supply.

The combination of all of the above factors complicates the analysis and description of timber supply. Furthermore, from the aggregate standpoint, often these distinctions may be lost in the actual process of data aggregation. If a given model fails to incorporate one or more of these distinctions, the validity and subsequent utility of its representation of actual timber supply becomes tenuous. However, the necessity for accurate information depicting timber supplies at all levels of geographic resolution remains. Marty (1969) summarizes the general utility of modeling timber supply from an aggregate perspective:

> *An aggregate timber supply model, using a classification of timber supply sources based on physical and economic characteristics and an intrasource projection technique which explicitly takes into account the more ultimate determinants of tree growth and removal, could be useful in predicting the supply response to various changes in economic conditions. The model would allow the analyst to estimate timber inventories under various assumptions about future prices and production costs. This information would provide an estimate of the change in total volume of stumpage that would become available under different future stumpage price expectations, thus providing a traditional long-run supply curve for timber. Similarly, it would be possible to estimate the effect on supply of changes in production cost factors like timber growing technology, labor costs, taxes, and so forth.*

SCOPE

This report describes the major analytical techniques utilized in aggregate timber supply analyses that are available in published or mimeographed form; it excludes numerous techniques developed for proprietary use in private industry and other methods currently being developed. Techniques examined are almost exclusively those developed for use in the United States or Canada, which are generally representative of available techniques. Fries et al. (1978) provide examples of long-term timber yield modeling in other countries.

[2]*Intended meanings of certain terms are defined in the Glossary.*

Analytical techniques for describing aggregate derived demand for timber, based on society's demand for products derived in part from timber, are not considered explicitly in this report. Therefore, the topics of price formation and projection are also not discussed.[3]

Because physical, economic, and institutional factors act simultaneously to influence aggregate supply, their representation in current analytical techniques must be considered. However, a specific breakdown of models along these lines is impractical, because many modeling efforts incorporate each of these three factors to varying degrees within their analytical frameworks. The following approach for describing analytical techniques is adopted in this report.

Aggregate timber supply analysis requires incorporation of the following processes:

1. Projecting changes in the forest land base.
2. Sampling and measuring the forest inventory according to various criteria and assembling inventory information to facilitate monitoring of changes in various inventory strata.
3. Projecting the growth and yield of the timber resource, including its response to varying degrees of management.
4. Projecting timber removals.
5. Projecting timber investment potentials and strategies over time.

This report describes existing analytical methodology in terms of four of the above areas. The collection and organization of timber inventory data (item 2 above) is not discussed in depth but is considered whenever it is relevant to the other areas noted above. Accurate inventory information is a critical input to the design and effectiveness of timber supply analyses. While the distinction between assembling inventory data and subsequent analysis of the data is not always clear, in this report inventory data will be regarded as the information base which underlies supply analysis and allows it to proceed. Detailed discussions regarding the nature of inventory data and other timber supply data may be found in Clawson and Stewart (1965), Davis (1976), Teeguarden (1977), Adams et al. (1979), Evans (1979), Eisenman et al. (1980), and USDA Forest Service (1981, 1982).

Institutional constraints in supply modeling are considered as they impact the forest land base and the establishment of output objectives (e.g., timber and water) from forest lands. However, techniques for analyzing supply in the presence of particular institutional harvest requirements (e.g., nondeclining even-flow) are only briefly addressed. Chappelle et al. (1976), Bell (1977), Johnson and Scheurman (1977), and Hann and Brodie (1980) examine some of the major techniques applied to analyze cases where these constraints exist.

[3]*Aggregate "demand" studies have historically estimated consumption quantities rather than demand functions, analogous to production estimates versus supply functions. See Gregory et al. (1971) for a review of "demand" projection techniques and Adams and Haynes (1980) for an example of combined supply and demand modeling for price projection.*

ORGANIZATION

The report first presents a historical overview of salient techniques that have been employed in analyzing aggregate timber supply. Current analytical techniques are then described according to four major component areas which contribute to aggregate timber supply analysis—land allocation, growth and yield changes of the timber inventory, harvest flows, and timber investment strategies. It is recognized that these components are not distinctly separate in theory or in their use in supply modeling. Such a classification does, however, permit the separation of areas in which specific techniques have tended to develop. This in turn facilitates the description of relative availability of methodologies and permits monitoring of progress of research in each of these four component areas. For each area, descriptions of specific models are provided as examples of current methodologies.

Following the discussion of modeling components, certain ramifications of data aggregation and uncertainty with respect to the reliability of timber supply projections are briefly explored, reflecting the fact that these aspects often seem to be inadequately addressed in aggregate timber supply studies. The report concludes with a general synthesis of relative strengths and weaknesses of existing timber supply methodology.

HISTORICAL REVIEW

Long-range studies of aggregate timber supplies in the United States originated with Hough's (1878, 1880) "*Report upon Forestry*" for the U.S. Department of Agriculture. Major studies that followed Hough's work are listed in Appendix A, which includes the date, primary analytical techniques employed, and scope of each study. Successive studies have in general been more comprehensive and reliable because of improvements in analytical techniques and data availability (USDA Forest Service 1982).

Quantitative determination of "growth and drain" guided major timber supply assessments (e.g., USDA Forest Service 1948) for most of the last one-hundred years. Difficulties inherent in rigid application of the "drain ratio" concept (ratio of current removals (harvest) to current growth) have been discussed by Vaux and Zivnuska (1952) and Bentley and Davis (1976), among others. For example, the drain ratio indicates changes in total volume of timber growing stock, but does not provide a measure of growth capability.

Until the latter half of this century, projections of aggregate timber supplies in published studies typically focused on physical measures such as growth, mortality, and removals, with little economic interpretation. The McSweeney-McNary Act of 1928 directed the Secretary of Agriculture to undertake comprehensive surveys of timber supplies to judge their capabilities in meeting timber "requirements" (Bentley and Davis 1976). Thus, USDA Forest Service studies under the McSweeney-McNary authority (e.g., USDA Forest Service 1948)

focused on a "balance of the timber budget of the United States," with maintenance of certain relative price trends of forest products.

One of the earliest systematic methodologies used for the projection of physical measures of aggregate timber supply was the stand projection method (e.g., USDA Forest Service 1965). Availability of computer technology and an improving data base in the form of relatively consistent timber inventory data facilitated the development and application of the Timber Resource Analysis System (TRAS) in the 1960's based on the stand table approach (Larson and Goforth 1970, 1974). Since then several other timber inventory projection techniques (e.g., individual tree based systems) have become candidates for use in regional timber studies; the major ones will be examined later in the section concerning timber inventory projection methodologies.

Economic measures of alternative timber supply levels were first used in the periodic USDA Forest Service appraisals in the 1970 *Outlook* (USDA Forest Service 1973). In this analysis, supply projections were based on balancing net growth and removals in the year 2000; utilizing this criterion, economically available supplies of softwood sawtimber were then estimated. The estimates of economic availability depended to a major degree on judgment rather than upon analytically derived relationships. Little attention was given to the timber management activities or total output level implied in a sustainable "net growth-removals" balance.[4]

The notion of supply and demand as schedules or functions (of quantities versus prices) was more thoroughly introduced into the decennial Forest Service assessments of timber supply in the 1980 Resources Planning Act (RPA) Assessment (USDA Forest Service 1982). Statistical analysis of the response of private stumpage supply to changes in prices and timber inventory levels was a basis for short-term harvest projections (Adams and Haynes 1980) in a comprehensive, interregional, economic equilibrium approach. In a different type of supply and demand analysis, the Forest Policy Project of the Pacific Northwest Regional Commission estimated private timber supply by maximizing present net benefits in conjunction with a downward-sloping curve for regional timber demand (Rahm 1981).

The gradual trend in aggregate timber supply analysis toward greater concern for economic variables was preceded by several seminal papers in the latter half of this century. Vaux and Zivnuska (1952) stressed the use of supply and demand concepts from neoclassical microeconomic theory, thus focusing not on single quantities, but on price-associated functions. Gregory (1955) undertook further theoretical investigations concerning economic timber growth goals, and Vaux's (1954) construction of cost-efficient supply schedules for California sugar pine represented some of the earliest empirical work in this area (Bentley and Davis 1976).

Timber supply schedules based upon the theoretical cost-efficiency concept have been used in numerous analyses since Vaux's 1954 study (Vaux 1973, Montgomery et al. 1975, Clawson and Hyde 1976, Jackson and McQuillan 1979). Use of statistically based modeling of aggregate timber supply trends has not been as widespread, in part because of problems with data availability. McKillop (1967), Adams (1974), and Robinson (1974) provide some of the earliest documented investigations of statistically based timber supply schedules. Use of statistical supply functions in a national timber assessment effort is documented by Adams and Haynes (1980), who also discuss integration of timber supply techniques within an overall supply and demand system that projects stumpage prices.

Duerr (1977) and Beuter (1979), among others,[5,6] critique past national timber reviews and outline major problems to be resolved in future timber planning studies. Major criticisms of recent domestic supply projection methodologies have centered on problems in adequately addressing (1) growth and yield impacts of shifting timber management strategies over time, (2) responses of nonindustrial, private timber supplies, and (3) aggregation with respect to factors that might affect future timber availability.

In summary, aggregate timber supply analysis has progressed from studies guided by application of the ratio of timber drain (removals) to growth, to comprehensive supply and demand modeling that involves projection of stumpage prices. Before the 1970's, projections of aggregate timber supplies typically consisted only of physical measures. The relatively recent modeling of timber supply and demand equilibrium has included statistically based stumpage supply schedules, with feedback mechanisms linking stumpage supply and timber inventory. Major criticisms of recent aggregate timber supply studies have been directed at the modeling of the dynamics of timber investment opportunities and investment behavior on nonindustrial, private lands, and also at aggregation schemes that impede disaggregation of results, provide uneven representation, and are difficult to use as a basis for policy formulation.

COMPONENTS OF TIMBER SUPPLY ANALYSIS

Depending upon the objectives and degree of precision sought in a particular study, varying degrees of abstraction are involved in analyzing the complex interrelationships of socioeconomic, physical, and biological elements of timber supply. For expository purposes, four components of aggregate timber supply modeling are discussed in this report: (1) land allocation, (2) progression of the timber inventory, (3) harvest flows, and (4) long-term investment or management strategies.

[4]*Problem analysis: Methods for analyzing national timber supply. By Thomas J. Mills, on file at Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo. 37 p. 1976.*

[5]*Critique assessment topic no. 1. Forecasting and RPA: 1980 RPA. By Dennis L. Schweitzer, Con Schallau, A. Schuler, Robert Stone, and Gregory Super, on file at USDA Forest Service Policy Analysis Staff Office, Washington, D.C. 1980.*

[6]*A critical analysis of timber supply research objectives for regional and national assessments. By John H. Beuter, on file at the Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo. 43 p. 1978.*

Interrelationships among the four components are quite important given that, in theory, their dynamic interactions necessitate a simultaneous solution in modeling. The dynamic context of a time path of interconnected components implies that modeling the progression of aggregate timber inventories cannot be effectively achieved without considering the time path of the decision variables for land use allocation and management. Furthermore, the composition of future timber inventories and harvests is strongly related to present management.

While segregation of timber supply analytical tools by these categories allows for a more straightforward discussion (corresponding to their typically separate treatment in the literature), such a segregation should not obscure the interdependencies among these components. Furthermore, considerations of the linkages of the four components to the overall economy are important in analyzing timber supply patterns, although such relationships have seldom been examined in depth (Adams and Blackwell 1973). Many of the more useful techniques and associated assumptions for analyzing these four timber supply components will now be examined.

1. LAND ALLOCATION

The quantity, quality, and location of land that will be allocated to timber production have generally been estimated exogenously in aggregate timber supply studies, as have the related ownership patterns and objectives of management. For example, exogenous projections of commercial forest area have been used in estimating stumpage supply in the Timber Assessment Market Model (TAMM); such projections are based on observed trends and subjective judgment (Adams and Haynes 1980). While Adams and Haynes recognize that the acreage devoted to timber production or allowed to remain in a forested state is not independent of the timber price and growth projections made in TAMM, they conclude that the decisions involving the many possible uses of land are too complex for direct inclusion as endogenous processes in TAMM.

Some exogenous projections of land use, as in the TAMM approach, treat land allocation to timber growing as a "residual" use that is calculated by sifting out other uses of perceived higher economic value (e.g., agriculture), along with institutional uses (e.g., wilderness), from the total potential base for commercial forest acreage (Wall 1981). This approach does not allow for modeling the dynamic interaction between changes in the forest land base and relative timber stumpage prices.

MODELING APPROACHES

Burnham (1973) used a Markov land use simulation model to depict intertemporal land use shifts in estimating future United States cropland availability. Forest land was one of six land uses projected, based upon land uses in the Southern Mississippi alluvial valley between 1950 and 1969. The finite Markov chain process involved estimating probabilities of land use shifts based on land movements between use groups over a historical time period, and then using these probabilities to project future land uses at alternative points in time. Projecting the future implications of past land use trends in this manner does mask the causative variables and, therefore, does not allow quantification of the processes underlying land use shifts.

In a study concerned with loss of wildlife habitat, MacDonald et al. (1979) also applied a Markov chain model to project bottomland hardwood acreages in the Lower Mississippi alluvial plain to 1995. Their probabilistic model was based upon historical land use data obtained primarily from interpretation of aerial photographs and other forms of remotely sensed imagery. Economic analysis in the study showed that agricultural crop production was more economically attractive than investments in natural bottomland hardwood stands or plantations.

Economic analysis of the allocation of land as an input or factor of production to timber growing has typically used the economic rent concept, with an unchanging alternative rate of return assumed for a particular forest ownership (e.g., Vaux 1973, Hyde 1980). Hyde (1980) applied the concept of land rent (i.e., net annual economic return per acre from a land use) to demonstrate the use of a variable land "production function." This function indicates land used for timber production at various prices and the associated efficient harvest levels. Hyde's land production function is based upon changing silvicultural technologies for each land class brought into production. As the various land classes receive different degrees of management intensity, different efficient yields per acre result. Access costs, dependent on distance to a site and topography, influence the degree of timber management applied to different land classes. This approach assumes that the landowner has a profit maximization goal, and that higher stumpage prices will attract less economically productive acres into timber production.

Access costs in timber supply determination are also addressed by Ledyard and Moses (1976) in a conceptual model of land use that combines transportation cost considerations (e.g., Bradley 1972) and capital theory. Their model of land use in long-run, steady-state, competitive equilibrium is based upon economic principles described by Von Thunen almost a century and a half ago (Von Thunen 1966). Von Thunen's model allocated land to alternative crops based upon yielding maximum economic land rents, given crop prices and transportation costs to market. Ledyard and Moses extend Von Thunen's basic framework to model dynamic aspects involving interactions of time and transportation costs, which have substantial implications for the use of capital in a forestry setting. Their focus, like Hyde's (1980), is on a long-run, steady-state equilibrium rather than on identifying the path to equilibrium.

No forestry-based models currently exist with the capability for modeling interregional linkages in land

allocation patterns involving forestry. A system for analyzing large-scale, interregional, agricultural land allocation, the Center for Agricultural and Rural Development (CARD) model, considers possible conversions of forest to cropland when estimating interregional shifts in agricultural production based on least-cost agricultural expansion to meet exogenous agricultural commodity requirements (Huang et al. 1981). However, the CARD model is presently not designed to estimate the possible reversion of cropland to forest.

GASPLY.—Georgia Supply (GASPLY) is an economic model designed to analyze forestry investments in Georgia (Montgomery et al. 1975, 1976; Robinson et al. 1978). The major theoretical bases of the GASPLY model—economic optimization procedures for land allocation models—are similar to those employed by Vaux (1973) and Hyde (1980). GASPLY estimates long-run equilibrium stumpage price and quantity and the associated total investment cost. Also estimated at this equilibrium point are the number of acres and owners involved, type of management (e.g., plantation) and location by planning district, and the site quality of the timber acreage. The criterion for GASPLY's economic optimization is maximizing present net worth of perpetual timber rotations.

The economic modeling of land use by GASPLY is based on the relative profitability of agricultural and timber production uses, assigning to a given land parcel the use with the highest economic rent (i.e., difference between all discounted relevant costs and revenues associated with production schemes into perpetuity). Limits are set on the amount of land that can shift between timber production and agriculture. Only the most productive timberland found in farmer ownerships is considered to be feasible for conversion to agriculture, while the amount of farmland available for conversion to timberland is restricted to idle farmland.

Idle land eligible for conversion to forest is assigned an opportunity cost (when calculating soil expectation value) equal to the economic returns that could be earned annually from alternative agricultural use of the land. Positive soil expectation values for timber production strategies cause such idle farmland to be converted to timberland in the GASPLY model. The agricultural opportunity cost is net of charges for clearing presently forested land, and the model allows for the possibility that idle farmland can revert naturally to timberland (i.e., custodial management). Similarly, land currently in timber production is shifted to agricultural use if associated soil expectation values are negative when alternative agricultural returns are considered.

Montgomery et al. (1975) recommend that commercial forest acreage of nonindustrial, private landowners be reduced in GASPLY input because of economically inoperable tracts (e.g., land around homesites). GASPLY adjusts land allocation patterns for expected population growth, with timberland shifting to urban-related land uses. The model can also reflect additional ramifications of urbanization, such as property tax changes. Impacted acres that are held in speculation (and will command high prices in the real estate market) are assigned higher ad valorem property taxes that may render timber production uneconomical.

GASPLY can adjust forest types within the timberland base to reflect the possibility that the timberland will receive custodial care in lieu of plantation or intensive natural stand management (Montgomery et al. 1975). Custodial management implies no active timber management other than continued harvesting and protection against fire, insects, and disease. For acreage assumed to receive custodial management, GASPLY applies an adjustment to the pine and oak-pine types for hardwood invasion.

In summary, potential timberland acreage subdivisions are evaluated by GASPLY under three timber management intensities—pine plantation, intensively managed natural stand, or custodial—and the management intensity producing the highest present worth is chosen for that acreage subdivision or cell if it can exceed an accumulated agricultural rent. The selected timber management levels and associated costs and yields are assembled into a long-run timber supply curve, which indicates the various amounts of timber that can be produced at different average unit costs.

ADDITIONAL MODELING CONSIDERATIONS

The long-run supply curve is based upon the criterion of economic efficiency on the part of the timberland owner—i.e., maximizing economic returns through timber production. It also embodies major assumptions that owners have (1) perfect knowledge regarding future timber stumpage price levels, yields, costs, etc.; (2) perfectly competitive stumpage and input (factor) supply markets; and (3) no entry barriers for timberland investments (other than cost). Furthermore, no dynamic-adjustment paths (and associated costs and price changes) and spatial detail are generally considered. These assumptions underlie most economic maximization models of timber supply (e.g., Hoyer 1975; Jackson and McQuillan 1979, 1980).

Land allocation based on neoclassical economic efficiency principles guided Davis (1972), Dideriksen et al. (1977), Hidlebaugh (1980), and Shulstad and May (1980) in estimating potentials for the conversion of forest land to agricultural uses. The fact that many of these land use conversion or investment opportunities have not already been undertaken suggests that the behavior of the diverse class of private landowners is not fully explainable with current economic efficiency models and data. A host of other studies of the behavior of nonindustrial, private forest landowners support this proposition.[7]

Modelers in general have had limited success in projecting patterns of land use (Voelker 1975); this is particularly true in the case of nonindustrial, private land management. The forestry literature is replete with observations on a related phenomenon often termed the "small forest owner problem." Numerous proposals for

[7] *Problem analysis: Improving the timber productivity of nonindustrial private forest lands. By J. E. deSteiguer, on file at Northeastern Forest Experiment Station, Forestry Science Laboratory, Princeton, W. Va. 37 p. 1980.*

attaining more "efficient" timber production patterns on these lands have been offered; some view this class of forest land owner as the key to significant increases in future national timber supplies (USDA Forest Service 1982).

The factors behind the apparent deviation of private landowner behavior from normative economic pathways have not been unequivocally identified, but may be the result of several combined characteristics of the market, owners, and analyses themselves. Imperfect market information, uncertainty, "noneconomic" goals, and lack of technical skills (Holley 1979) are examples of possible confounding market and owner-related factors. An important analytical shortcoming may be the present inability to account fully for all the relevant returns, especially nonmonetary benefits, and costs accruing to a landowner from alternative land uses.

This latter problem may arise primarily from data deficiencies and/or measurement errors; however, the analytical approach and theoretical foundations may also be partially at fault. In a study of New England landowner behavior, Binkley (1979, 1981) applied a "utility maximization" approach which accounted for the influence of some nontimber outputs in timberland management decisions. Boyce (1977, 1978) has also developed techniques for describing timber management activities in the context of multiple benefits. While these approaches have not been extensively tested, limitations to wider application in the short term appear to center on data deficiencies. The lack of accessible joint production data at aggregate levels, combined with inherent aggregation problems resulting from resource systems which have both varying ecological and economic bases, has greatly hampered aggregate multiresource production analysis. Problems of even greater severity on the demand side further render integrated forest resource analysis a very difficult task at aggregate levels.

Deviations of timber suppliers from norms prescribed in the formulation of optimization models based on financial maximization prompted Marty (1969) to recommend a modeling technique adapted to multigoal or mixed goal analysis. His recognition of the difficulty of this task is still relevant today. While some progress has been made over the last decade, modeling problems related to incommensurable objectives held by many timberland owners strongly influence all four dimensions of timber supply analysis referred to previously. This contributes substantially to uncertainty in timber supply modeling (see section, Aggregation and Uncertainty Considerations).

Projection of land use allocation based on historical relationships among economic and other important variables is one alternative tool to complement economic efficiency models. However, few statistically based models of forest acreage trends have been employed, primarily because of substantial data problems. Adequate time series data for forest land use on which to base statistical functions are difficult to construct because of irregular measurements or estimates of commercial forest land in the past. Timberland acreages for a particular state are estimated approximately every ten years by USDA Forest Service Forest Inventory and Analysis surveys (e.g., Knight 1973). Survey cycles differ among states. Attempts to augment periodic Forest Service forest acreage data with other major data sources is hindered by differing criteria used in past classifications of forest lands.

White and Fleming (1980) relied upon farm woodland data estimated every five years in the Census of Agriculture (e.g., USDC Bureau of the Census 1977) in analyzing factors underlying competing land use shifts in Georgia. A system of equations was statistically estimated to explain simultaneous changes in crop, pasture, and forest acreages. The most significant determinants of forest acreage were the amount of land in farms and farm crop acreages for previous years (Fleming 1980). Regression results were used in a simulation model to investigate the impact of government land diversion programs on land use patterns from 1980 to 2000.

In summary, the fundamental question of the allocation of land as an input to timber production has been analyzed using several distinct approaches in aggregate timber supply studies. National timber assessments have generally used exogenous estimates of timberland acreage, based on computations of forest land as a residual use (e.g., USDA Forest Service 1982). The dynamics involved in the joint determination of the timberland base and relative timber stumpage prices have not been modeled, nor have similar interactions with other sectors, particularly agriculture. In short, forecasting the availability and accessibility of forest acreage is a major problem in aggregate timber supply analyses.

2. TIMBER INVENTORY PROJECTION

A number of methods have been developed to project future levels of timber inventory (growth, mortality, accumulated stock, and structure) as it would occur in an unmanaged forest, as well as in response to certain management practices (Avery and Burkhart 1983). Such methods of projecting forest development can be divided into two broad classes—direct and indirect—based upon whether the method is applied locally to the same stand from which the data used for projection purposes are obtained (direct methods), or whether sample data for numerous stands are synthesized and then extrapolated to other stand conditions (indirect methods).

There are many models designed to project timber inventory development, some of which are outlined in appendix B. These models have been developed for numerous species and regions; however, models for a single species may vary considerably, for example, in terms of the sample of stand conditions on which the model is based or the analytical methods employed. Evaluation of these models requires the synthesis of many quantitative and qualitative factors (Buchman and Shifley 1983). Surveys of inventory projection models are also provided by Williston (1975), Solomon (1977a),

Farrar (1979a), Dudek and Ek (1980), Burkhart et al. (1981), Moeur and Ek (1981), Trimble and Shriner (1981), and Hann and Riitters (1982).

DIRECT METHODS

Direct projection methods are those in which the results of operations performed upon a data sample are applied directly back to the population from which the sample was obtained, and only to that specific population. The most familiar of these methods is that of stand table projection, in which a sample of growth rates is obtained from a given stand and then applied directly back to that stand for projection purposes.

Stand tables are composed of frequency data showing number of trees according to such classification systems as species, diameter at breast height (d.b.h.), or height classes (Husch et al. 1972). Stand tables, commonly expressed on a per acre basis, are useful in depicting the stand structure or distribution of tree sizes and species in a stand. Stand table projection models use estimates of future diameter growth, removals, mortality, and ingrowth to adjust the stand table in an accounting fashion over time. Husch et al. (1972) further discuss the basis and the advantages and disadvantages of the general stand table projection method.

Although stand table projection models may be used to address localized, individual stand development questions, they have also been used for projecting aggregate timber supplies when forest-level or aggregate stand questions are being investigated. To answer these broader forest-level questions, the assumption is made that a large, regional inventory can be treated as one all-aged stand.

These generalized stand table projection models can use conventional timber inventory data and may be relatively simple and inexpensive to use. Some of their disadvantages are that they need a large data base, pose difficulties when different forest management schemes are being modeled, and are conceptually difficult to interpret. Another disadvantage is that, because the forest is modeled in aggregate, reliable tree size and distribution information for smaller areas is hard to extract. The following example of a stand table projection model expands on some of these points.

TRAS.—The Timber Resource Analysis System (TRAS) developed by Larson and Goforth (1970) has been employed as the inventory projection system for many recent USDA Forest Service timber assessment studies at the regional and national level (e.g., USDA Forest Service 1982). TRAS has continued to evolve since its inception in the 1950's, and an expanded version, TRAS-1980, is described by Alig et al. (1982). TRAS is a stand table projection model specifically designed to solve three types of problems: to reconcile differences among forest surveys, to update forest surveys completed at different times to a common compilation date, and to project long-term timber inventory changes.

The TRAS system includes both an exponential size class distribution model, the Q method, and a parabolic size class distribution function, the non-linear interpolation method or NLI method (Larson and Goforth 1974). In relatively large aggregations of individual even-aged and uneven-aged forest stands, the overall stand table of number of trees by diameter class will approach an exponential distribution, for which the Q method is appropriate. The NLI method was designed to model the parabolic-type size class distribution of even-aged stands. Because collections of stands are modeled in aggregate, timber supply studies and such aggregates tend toward the exponential distribution (or the inverse J-shape as shown in fig. 1); thus, only the Q method or exponential distribution model is discussed in this report.

The Q method of TRAS is based on Meyer's (1952) observation that a graphical representation of the diameter distribution in any large forest area, with a mixture of stand sizes and ages, tends toward an inverse J-shaped curve (fig. 1). This curve is expressed as an exponential function that relates the number of trees per acre to their respective d.b.h. class. Thus, an average annual increase in diameter is related to a corresponding potential increase in the number of trees. This distribution seems to be generally true for the aggregation of even-aged, uneven-aged, or mixed stand distributions.

The aggregation capabilities of TRAS's inventory projection system depend largely on the assumption that aggregate "stands" constructed from a pooling of data from much smaller geographic subdivisions are an adequate representation of the combined smaller units, as gaged by the objectives and accuracy requirements of the particular timber supply study. In practice, TRAS is often applied to aggregates that represent millions of acres. Empirical verification of adequate representation by such aggregates is quite elusive because of the unavailability of independent and appropriate data bases upon which to check regional abstractions. Larson's test using South Carolina data did indicate that as few as ten Renewable Resource Evaluation sample plots were needed to contruct a "sound" stand table for TRAS projections.[4]

The potential increase in inventory, due to growth of a stand, is computed as the annual per acre change in the number of trees in each 2-inch d.b.h. class (fig. 1). The overall change in inventory is obtained by subtracting the annual removals and mortality from the just-computed potential increase in the number of trees. This resulting number of trees added to the inventory is converted to a total volume by using the average volume per tree by d.b.h. class and the area of commercial forest land (Larson and Goforth 1974).

To prevent the development of unrealistically high inventory basal areas during projections, a set of constraint equations has been developed. As described by Larson and Goforth (1970), this set of equations reduces the radial growth and ingrowth and increases the mortality as the total softwood and hardwood basal area increases. The overall timber inventory in a region has generally been projected as two separate softwood and hardwood "average" stands by the TRAS model in aggregate timber supply analyses, although the projections of both stands are influenced by the total stand basal area constraint.

The mechanics of the TRAS projection system are relatively simple, and the accuracy of TRAS inventory projections essentially depends on the ability to adequately project radial growth, removals, and mortality, by diameter class, and by ingrowth.[8] TRAS was designed to project timber management levels that are implicit in the radial growth, mortality, removals, and ingrowth data that comprise the bulk of the input to the stand table projection process (i.e., TRAS contains no growth, mortality, or removal rate coefficients internally). Thus, the implicit assumption behind the standard TRAS inventory projection is that timber management will be implemented at basically the same level over the projection period as that which formed the historically based stand table input. This assumption regarding projected TRAS parameters has been strongly questioned because of apparent trends in intensifying timber management to a degree different from that implied by standard TRAS projections.[8]

TRAS procedures were modified in the 1980 RPA Assessment to incorporate impacts of such managment shifts (Barber 1980). The management shifts, based on identified timber investment opportunities, were translated into growth increments via Barber's modification of radial growth and mortality rates in TRAS's stand table. The modification procedure is of an ad hoc nature and was devised to fit an immediate need of the 1980 RPA Assessment modeling. The cumbersomeness and difficulty in monitoring involved in TRAS's modeling of

[8]*Problem analysis: Timber supply analyses for RPA Assessments. By Darius M. Adams, on file at the Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo. 29 p. 1980.*

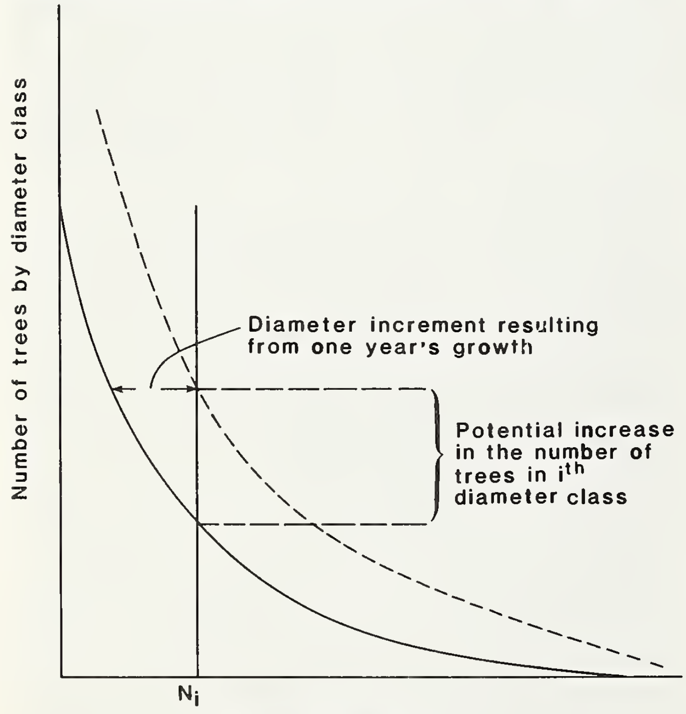


Figure 1.—Inverse J-shaped form of diameter distribution assumed in TRAS model for large forest areas with mixture of stand sizes and ages, with diameter distribution displacement shown for one year's growth (Larson and Goforth 1974).

shifts in timber management intensity is one of the major reasons that the USDA Forest Service plans to supplant it, at least in some regions where management shifts are significant, for the next major national timber supply assessment.[8] This was prompted by the need to examine policy questions that frequently involve changes in timber management practices or intensity.

The use of TRAS to evaluate certain changes from the initial state over long projection periods has also been questioned.[9] For example, in a shift from an inventory of predominantly old growth to largely young growth, such a transition could cause the lower d.b.h. classes to shift from predominantly suppressed to predominantly dominant crown classes. The corresponding acceleration in growth over time reflected by the TRAS model may not be an adequate representation of this change. The occurrence of such deviations from steady-state systems has led to suggestions that TRAS be limited to short-run inventory updates in some parts of the country.

Other reported limitations in the application of TRAS in some timber supply analysis tasks have seemingly increased with the marked evolution of timber supply modeling and associated needs in recent times. In part, some applications of TRAS extend beyond those originally intended in its design. For example, Row (1977) points out severe limitations of TRAS with regard to the previously mentioned insensitivity to trends in management levels and investment in timber growing activities, as well as environmental and multiple-use constraints. While noting that the TRAS system has been validated reasonably well in decade-by-decade biological projection of timber inventories for which it was designed, Row asserts that several major timber supply investigations (Adams 1975, Holley et al. 1975) have employed TRAS as a timber inventory projection module primarily because there was no other model available with adequate supporting data.

With respect to these criticisms of TRAS, the use of "average stands" to analyze broad regional areas has been regarded as acceptable when detailed input parameters for smaller areas are lacking or when there is no need to know how small parts of the total resource are changing with time (Oswald 1978). The basic assumption that a large regional inventory can be treated as one large, all-aged stand may be reasonable in some parts of the country. The assumption that a large, all-aged stand represents a regional timber inventory structure is questioned, however, when even-aged management is widely practiced and clearcutting is the accepted harvest method.

Two methods have been proposed to minimize the above weakness. One proposal is to divide the inventory into discrete strata and to use the TRAS model to project each stratum separately (Oswald 1978). The second proposal is to divide the inventory into discrete strata and to use the TRAS stand table projection technique for the older strata and to use a yield table projection technique for stands regenerated under more intensive even-aged management.

[9]*Personal communication with A. R. Stage, USDA Forest Service, Moscow, Idaho.*

Alternative approaches to the TRAS system for use in regional timber inventory projections include the Timber Resource Inventory Model (TRIM) and the Southern Pine Age-Class Timber Simulator (SPATS), models that currently are being developed and tested. The TRIM model employs a more disaggregated approach than TRAS, as it stratifies timberland acreage by age classes, site, species, management intensity, and stocking level (Tedder 1983). Acres can be shifted into different levels of timber management in two ways (1) prespecified management shifts over the entire planning horizon or (2) management shifts based on economic investment behavior estimated internally by the model. Yield table projections for ten-year age classes for these different levels of timber management are made using an approach to normality technique.

The SPATS 5-year age-class model is intermediate between the TRAS and TRIM approaches in regard to level of aggregation. It can model three different forest types separately for the Southeast and Midsouth: (1) planted pine, (2) natural pine, and (3) oak-pine (Brooks 1983a). One average site class and stocking class are used and an approach to normality is also utilized to adjust for stocking variations. Reforestation practices can be directly simulated in the SPATS model, including estimating annual planting over a period by using equations developed using historical data (e.g., cost-share subsidies).

INDIRECT METHODS

Indirect timber inventory projection methods are based on a range of growth and/or yield observation samples that are utilized in estimating the parameters of projection models. The resultant models are then applied to subject stands larger in nature than those from which the original growth/yield data were obtained. In essence, therefore, these methods rely on a two-phase process: the first provides or describes the data to which the projection model is to be applied (i.e., the inventory stands or plots); the second sample provides the data for model construction, and for that reason it is more detailed than the former. The model is then applied back to the first sample for drawing inferences about the entire forest studied. Indirect models may be described in terms of two broad classes:

A. Whole stand yield tables
   1. Normal
   2. Empirical
   3. Variable density
B. Variable density growth and yield models
   1. Whole stand
   2. Size class and/or growth component
   3. Individual-tree
      a. Distance-independent
      b. Distance-dependent

Whole Stand Yield Tables

Yield tables describe stand development and yields by age, site quality, and, on occasion, other descriptors. The most familiar examples of such tables are those described as normal yield tables, which attempt to describe the aggregate or whole stand yield of "fully stocked," undisturbed natural stands by site index and stand age. Such tables are constructed from measurements of many stands, but the stand characteristics are observed only at a single point in time; thus, they provide estimates of net production only (Curtis 1972). The pattern obtained by plotting yield or stand characteristics over age is assumed to represent a real growth pattern for stands of this density. While they have the advantage of being relatively easy to construct, this is generally outweighed by the fact that most normal yield tables are only applicable to relatively pure and even-aged stands, and they provide information only on aggregate stand variables. Such tables do not adapt well to management purposes, and they are also difficult to use for "non-normal" stands.

A variation on normal yield tables are empirical yield tables, which are constructed on the basis of average stand stocking conditions, as opposed to fully stocked stands. Such tables are constructed from sample plots with varying degrees of stocking, with multiple regression techniques generally utilized to determine average stand characteristics. While these tables allow for somewhat greater flexibility in projecting stand yields, they still do not overcome most of the difficulties stated above with respect to normal yield tables. Another important disadvantage of most such yield tables is that they provide relatively little information on stand growth. While yields are furnished for the "terminal" stand condition (i.e., end of the projection period), little information is provided on initial stand conditions and growth patterns that resulted in these terminal yields. This greatly reduces the utility of most yield tables for comparing management alternatives.

Variable density yield tables are the result of attempts to resolve these problems concerning growth representation in timber inventory projection modeling. Such tables provide yields for a range of stand densities for each age and site combination. However, early variable density yield tables were based on only single-point-in-time observations, and did not effectively provide further information on growth patterns. More recently developed variable density growth and yield modeling techniques reflect the incorporation of growth data from permanent plot records and corresponding equations to characterize forest growth as well as its integral forest yield. Variable density growth and yield tables have been geared primarily to silvicultural alternatives in forest management (Ek and Dudek 1980).

Variable Density Growth and Yield Models

Variable density growth and yield models are constructed to provide both growth and yields corresponding to different stand densities. They generally include specific growth functions, as well as yield functions derived from the integration and/or summation of growth functions. Such models may be utilized for the

construction of variable density yield tables, and thus they are of great value in contributing to the ability to represent potential results of different silvicultural management alternatives.

Whole Stand Models

These techniques have generally utilized differential equations to describe the rates of change of various components of stand development. An important initial study in this area was that of Buckman (1962), in which the growth rate of even-aged stands was expressed as a function of age, site, and stocking in a differential expression. With this approach, yields are obtained by integrating the growth rate equations over time. Depending upon the specific form of the rate model, differentiation may be employed to derive stocking levels which maximize growth.

Another significant study that exemplifies important elements of this approach was that conducted by Clutter (1963), in which growth rate models were developed and subsequently integrated to provide closed-form expressions for yield predictions. Data for this analysis were obtained from 5- and 10-year remeasurements of thinned permanent plots of loblolly pine. The first phase of the analysis involved the development of regression equations to predict per acre cubic foot and basal area yields from age, site, and basal area. Regressions for basal area growth and cubic foot growth were then used to obtain prediction equations for future basal area and cubic foot volume of a given present stand; this was achieved by integration of the aforementioned growth equations with respect to age. Sullivan and Clutter (1972) later revised Clutter's (1963) loblolly pine model and addressed two statistical problems: (1) dependent parameters within a system of equations and (2) observations from remeasured permanent plots that are not independent.

Size Class and/or Growth Component Models

Other techniques which utilize differential equations to model forest development may project growth components by size or diameter classes. Moser's (1974) system of nonlinear differential equations for predicting ingrowth, survivor growth, and mortality by diameter classes exemplifies this modeling approach (see also Moser et al. 1979). An additional example is the SHAF simulation model (Adams et al. 1974, Ek and Monserud 1979), based upon a stand table projection system modified to incorporate stand growth component equations given by Ek (1974) and later by Adams and Ek (1974).

Input for the SHAF model includes site index and number of trees by 2-inch diameter classes. Three components of stand growth by diameter classes are then estimated using nonlinear difference equation models. These components include ingrowth, upgrowth (i.e., number of trees rising from one diameter class to the next higher class), and mortality. Given these three growth component expressions, the number of trees in each diameter class at the end of a given growth period may be obtained. By applying conversion factors to the number of trees in each diameter class, basal areas and volumes for each class may also be calculated. It should be noted that variations within different models may be manifest in different forms for components representing survivor growth, mortality, and regeneration.

Individual-Tree Simulation Models

A common characteristic of the preceding kinds of variable density growth and yield models is their reliance upon aggregate stand or size class characteristics such as basal area or number of trees for modeling of forest development. The most recent approach for modeling forest growth and yield consists of individual-tree simulation models, in which stands are described on the basis of characteristics of individual trees, which then may be combined to form stands. These models consider a set or list of individual trees and associated tree characteristics for a plot and simulate the growth of each tree by explicit or implicit "potential" growth functions; these, in turn, are modified by expressions reflecting tree size competition (Ek 1977). In this manner, tree spatial locations and individual tree characteristics influencing tree growth and resultant yields may be explicitly considered. Individual-tree models may be divided into two general classes: (1) those that are independent of intertree distances, and (2) those that require intertree distances as a necessary input (Munro 1974).

Distance-Independent Models.—Individual-tree distance-independent models do not require intertree distances but classify the competitive status of the subject tree by comparing its characteristics (size, crown ratio, etc.) in relation to all other trees in a sample plot. Each sample tree is weighted with an expansion factor to indicate the number of trees per acre it represents.

The advantages of this type of model are that inputs consist primarily of conventional inventory data (although some modifications are required); it can model any age structure or species mixture; and it provides relatively detailed information on tree and stand parameters and on the effects of stand management. Disadvantages of this kind of model include its relative complexity and the inability to predict the growth of specific single trees with any reliability (Munro 1974). It should be noted that all of the individual-tree models described herein are similar in that they involve some type of tree accounting, product conversion, and summary capability, with the actual stand dynamics treated by specific program sections or subprograms for survivor tree growth, mortality, and, sometimes, ingrowth or regeneration. Somewhat distinct from this dynamic part of the model, there may be subprograms for management activities, such as harvesting or thinning. Other models have identified specific options for insect and disease impact studies and habitat analyses.

Individual-tree distance-independent models have been employed to simulate growth and yield for in-

dividual forest stands, small forested areas, and for entire states. Criticisms are sometimes voiced, however, concerning the aggregation capabilities of these models as well as the potential costs of adapting them to such large-scale assessments. The extent to which the number of plots needed to represent forest conditions of interest would expand in moving from substate to regional or national timber assessments requires further examination, as does the attendant cost and accuracy of the resultant biological modeling. Conversely, an individual-tree model capable of projections for 20 species may be no more complex (and probably less so) to construct and use than 20 "simpler" models for 20 different species.[9] The difficulties inherent in combining diverse growth and yield models are well known to resource projection analysts.

Individual-tree distance-independent models have been developed by Lemmon and Schumacher (1962), Botkin et al. (1972), Goulding (1972), Stage (1973), and USDA Forest Service (1979), among others. Two examples of this type of model are described below.

STEMS.—An individual-tree distance-independent model considered potentially useful for regional or national analyses is the Stand and Tree Evaluation and Modeling System (STEMS), formerly known as the Forest Resources Evaluation Program (FREP) (USDA Forest Service 1979, Hahn et al. 1979, Moeur and Ek 1981). STEMS is a forest growth model designed to describe stand development, with or without management activities. The model's timber growth projection system has been applied in the Lake States (Smith and Raile 1979, Jakes and Smith 1980) and is being tested in the Pacific Northwest; plans exist to calibrate it for use in the Central States and Southeast as well.

STEMS will handle a variety of forest conditions including pure or mixed stands. Growth and yield for even- and uneven-aged stand conditions can be simulated if the relevant biological response equations have been developed and tested for the particular geographical area. STEMS can be used to (1) update or project plot tree lists to a future time, or (2) evaluate various silvicultural management alternatives. The model has numerous timber management options available.

STEMS uses basic inventory data or data from other sources such as stand and stock tables to construct an input list of individual trees representative of the forest condition of interest. This tree list contains species, diameter at breast height, crown ratio, and an expansion factor (per acre) for each tree. If crown ratio is missing from the input list, it is approximated by using a relationship with diameter and basal area.

The model's operational portion, which uses growth equations for individual trees to transform the input tree list into an updated output tree list, has three parts: potential growth function, modifier function, and mortality function. The potential growth function estimates how rapidly trees would grow in d.b.h. if they did not interact with other stems. The modifier function reduces the potential change to correspond with observed data from permanent growth plots. The mortality rule computes a probability of death for a tree based on its species and growth rate.

Output from the model is a list of trees showing species, new d.b.h., and new status if the tree dies, plus associated product conversions and summary tables of stand characteristics. The projection system does not currently handle events such as ownership changes.

Prognosis.—In addition to STEMS, another individual-tree distance-independent model with potential for aggregate timber supply analyses is the Prognosis model for stand development (Stage 1973, 1979; Stage et al. 1980). This model has been extensively used in the northern Rocky Mountains. It has been adapted to all major tree species found in Idaho for both even-aged and uneven-aged stands and may be applied to similar coniferous types found in the Pacific Northwest.

The Prognosis model predicts future development of stands through displays of long-range values of tree diameters, heights, crown ratios, tree species composition, and understory shrub composition and coverage. Like the STEMS model, Prognosis uses species-specific, internal growth equations to simulate the growth and yield of individual trees, which can then be extrapolated to a stand basis. As with most individual-tree models, it is not restricted to specific cover types; rather it is applicable to stands containing any mixture of species or age and size classes that grow as a community (Stage 1973). Additional capabilities include conversion of tree dimensions to conventional units of timber yield in total cubic and board feet, as well as information related to wildlife habitat changes, watershed protection, and recreational values that can be derived from the fundamental tree and shrub variables.

The Prognosis model consists of a set of computer programs for combining current silvicultural knowledge with past growth data to make a forecast of stand development reflecting the effects of thinning, fertilization, and regeneration harvests. This program is capable of making projections for a period as long as a full rotation.

Input to the Prognosis model consists of habitat type, shrub cover and height, and conifer stocking. Input tree lists are described by species, d.b.h., and crown ratio. Removal of individual trees from an inventory plot are used to reflect harvests. The model depicts tree growth through a collection of submodels representing growth of trees at different stages in their life cycle. These stages are as follows:

1. Regeneration establishment that follows seedlings through the first 10 years of growth.
2. Regeneration development that represents growth of established seedlings and saplings up to the time they reach 5 inches d.b.h.
3. Poles and larger trees.

The regeneration establishment submodel predicts the stocking characteristics of small (1/300 acre) plots. This modeling of stocking rate requires inputs describing habitat type, slope, aspect, elevation, topographic position, time since disturbance, site preparation method, overstory composition and density, planting, and distance from seed source.

The regeneration development submodel predicts height and diameter increments of trees less than 5 inches d.b.h. Height increment is modeled using the height and species of the subject tree, overstory density,

conifer and shrub competition, habitat type, slope, aspect, and elevation. The diameter increment is a function of species height and predicted height increment.

The growth of pole and larger trees is represented by a set of species-specific equations that predict diameter increments from values of diameter, crown ratio, crown competition factor, basal area in trees larger than the subject tree, slope, aspect, elevation, habitat type, and geographic region. The height increments of these trees are dependent on predicted diameter increment, height, diameter, and habitat type.

The Prognosis model specifies mortality as a function of species d.b.h. and stand density (Hamilton and Edwards 1976). As with the growth functions, these relationships should be based on data from the area to which the model is to be applied.

Output from the Prognosis model is separated into individual tree summaries and forest stand summaries. Individual tree records consist of species, d.b.h., crown ratio, past diameter growth, and trees per acre associated with each of the original sample tree records. Forest stand records consist of numbers of trees per acre, distribution of d.b.h., volume characteristics of the total stand in cubic feet, surface areas of boles in square feet, and accumulated tree height. In addition, total cubic foot volume representing the growth of the initial tree population and the total cubic foot volume representing mortality are summarized (Stage 1973).

The Prognosis model has the capability to represent effects of pest populations (e.g., Douglas-fir tussock moth) on growth and mortality (Crookston 1978, Monserud 1978, Monserud and Crookston 1982). It may also be utilized to resolve discrepancies between inventory growth rates and model-based estimates, and to rescale model-based growth and mortality rates to represent nonmodeled silvicultural treatments such as fertilization or reduction in shrub competition. A parallel-stand growth processor permits interstand effects such as harvest allocation or pest contagion to be represented.[9]

Distance-Dependent Models.—The second type of individual-tree model requires intertree distances as a necessary input. Some representative distance-dependent models have been developed by Newnham (1964), Mitchell (1969), Arney (1974), Ek and Monserud (1974), and Daniels and Burkhart (1975).

In these models, "individual trees" on a plot are assigned certain initial size and spatial distributions. The trees are then "grown" according to some function of their size, site, competitive status, and sometimes a random component representing microsite and/or genetic variability. Competitive status for each tree is quantified in terms of a competition index that is a function of the tree's size and the distance to and size of its neighbors. Mortality is regulated as a function of competition index, tree size, and/or growth. Yield estimates are made by applying volume equations to the dimensions of the trees (Curtis 1972), as in other individual-tree models.

Individual-tree distance-dependent models may provide more detailed stand and tree measurements than distance-independent ones. Several disadvantages of this type of model are that they require (1) intertree distances as an input (this is usually not collected as inventory information), (2) a meaningful competition index for individual trees, and (3) more computing time.

Individual-tree distance-dependent models can be considerably more sensitive to harvest treatments and reproduction response than diameter class models (Ek and Monserud 1979). However, Ek and Monserud also suggest that whole stand models may project aggregate stand characteristics almost as well as individual-tree distance-dependent models at a much lower cost, within the range of data used to construct the former. Because of their detail and flexibility, individual-tree distance-dependent models may be most useful in analyses of optimal silvicultural alternatives (Adams and Ek 1974).

Although the growth and yield estimates are considered to be fairly accurate, currently the greatest obstacle to the use of these models for state and regional analyses are the data requirements for intertree distance coordinates and the expense of the required computer time. Another disadvantage is their use of stochastic methods for deducting mortality.[9] As a consequence, the outcome of the simulation is itself a random process that should be replicated to estimate the expected value. For long-term projections or for high mortality, the variance of the output depends on the initial numbers of tree-records in the simulation.

PTAEDA.—The model PTAEDA, developed by Daniels and Burkhart (1975), is representative of the single-tree distance-dependent models. PTAEDA simulates the growth of loblolly pine under a wide range of management alternatives.

The two major subsystems in PTAEDA deal with the generation of an initial precompetitive stand and the growth and dynamics of that stand. After PTAEDA was developed for old-field stands, management subroutines for unmanaged plantations were developed to simulate the effects of site preparation, fertilization, and thinning (Daniels and Burkhart 1975). Trees are "grown" annually according to their size, site quality, and intertree competition. The probability of survival for each tree is calculated from a function relating each tree's individual vigor and its competitive stress as measured by estimates of photosynthetic potential. This probability is used to stochastically determine annual mortality.

Effects of certain management practices are incorporated into PTAEDA by modifying the original growth function. The efficiency of a site-preparation program is expressed as the degree to which a cutover site approaches old-field conditions. Growth reductions on cutover land are assumed to be solely due to competing vegetation, because degradation in site quality caused by past management practices could be described by initially specifying a lower site index (Daniels and Burkhart 1975).

Similarly, the response to fertilizer treatments could be described as an increase in site quality, as suggested by Ek and Monserud (1974) and Hegyi (1974). For this reason, a site adjustment factor that acts as a multiplier for site index for fertilized stands is built into the model.

Intermediate thinnings result in a decrease in competitive stress for the remaining trees. These trees become more capable of competing for the limiting

resources such as light, water, nutrients, or growing space. The response to these thinnings is moderated by a tree's own potential for growth as measured by a function of crown size (Daniels and Burkhart 1975).

Estimates of basal area per acre, trees per acre, total stem cubic foot volume, and total aboveground biomass are also given by PTAEDA. To further describe stand conditions, the output summary includes the mean, standard deviation, and range of relevant tree dimensions; the stand diameter distribution; the average height of each diameter class for live trees; the trees removed in thinning; and the trees lost to mortality. Farrar (1979a) indicates predicted yields agree with published reports for thinned and unthinned old-field plantations.

SUMMARY

Direct inventory projection methods have been used in most large-scale timber supply analyses. The utility of the TRAS model (Larson and Goforth 1970, 1974) has been demonstrated in the last several USDA Forest Service timber assessments. Although TRAS is fairly inexpensive to run, can represent any geographical level by the use of "average" acres, and has a projection system with fairly simple mechanics, it has been criticized in several respects. A major criticism is that TRAS is not very tractable as a tool for simulating changes in timber management intensities.

Among indirect methods for inventory projection, individual-tree distance-independent models have often been proposed as a replacement for TRAS. These models have the capacity to efficiently simulate silvicultural operations as well as to provide regional growth and yield projections. Models of this type that have proven most useful are the STEMS model (USDA Forest Service 1979) and the Prognosis model (Stage 1973).

The individual-tree distance-dependent models are capable of providing accurate growth and yield projections as well as detailed information about stand structure (e.g., Daniels and Burkhart 1975). Conversely, the large data requirements of intertree coordinates and excessive computer time have thus far prohibited use of these models for large-scale analyses.

Although the "inventory projection" models discussed were designed for somewhat different purposes, various opportunities exist for linking them in regional or national timber supply studies. For example, individual-tree-based models, such as STEMS, may be more precisely classified as variable density growth and yield table generators. They could provide "harvest scheduling" models with the necessary timber growth information to help drive an overall timber inventory projection system. Expanded and improved regional growth and yield modeling by such techniques will depend largely on progress in assembling growth and yield data in a consistent manner for all regions, which would facilitate modeling of alternative timber management possibilities. In particular, it is important that growth and yield model output forms be similar.

3. HARVEST FLOWS

Harvest flows represent the timber volumes removed over time from existing timber inventories or stock supplies of stumpage. The modeling of these flows is the central concern of aggregate timber supply studies. Linkages among harvest flows and the two components of aggregate timber supply analysis discussed previously—land allocation and timber growth and yield—involve dynamic interrelationships between biological and economic forces. Furthermore, because timber inventory is both invested capital and product, modeling of harvest flows is also conceptually linked to timber investment processes that impact future inventories from which harvests will be drawn.

This intertemporal linkage of harvest decisions and longer term investment decisions may involve adjustments in timber inventory structure and volumes to achieve long-term objectives, such as profit maximization, with investments (e.g., fertilization) or disinvestments (e.g., harvest) based strongly on future expectations of the timber economy. Timber market fluctuations in the short term may prompt previously unforeseen revisions of long-term adjustment paths so that short-term gains may be realized. Navon (1982) observes that the time path of aggregate harvest responds to market conditions when present net worth is maximized, as would be the case with industrial and some nonindustrial private ownerships. For public agencies, however, this path is manipulated to provide a stable supply of timber and/or other socially dictated objectives.

Thus, the timing and intensity of harvests chosen by an owner are major decisions in long-run timber management strategies, and their estimation greatly influences the projected results of other analytical components in timber supply studies. In theory, harvest patterns would be chosen to maximize discounted economic returns over an infinite time horizon, if the owner's goal were profit maximization. However, the planning horizons which underlie actual harvest decisions vary greatly among owners with respect to short-run versus long-run perspectives. These differences can be attributed primarily to varying financial flow needs and uncertainty regarding financial returns from various forest management strategies.

While marked differences among harvest patterns and length of planning horizons exist for the numerous types of forest land owners, the flexibility in timber resource adjustment and harvest over time is constrained to a large degree by underlying biological and economic processes of timber production. Distinguishing between short-run and long-run situations in aggregate timber supply analysis is somewhat problematic, especially in view of the long production periods inherent in timber production. In an economic context, the short run is characterized by the presence of a fixed production factor, while in the long run all factors are considered variable. Lyon and Sedjo (1983) observe that in forestry the short run embodies a perspective of timber production in which timber manifests many characteristics of a nonrenewable resource. In this context, the question of

short-run supply relates to the rate at which the existing stock is harvested.

Duerr (1960) also proposes temporal characterizations or conditions for timber supply: stock supply, short-run supply, and long-run supply. Stock supply of stumpage arises from existing timber inventory and, because the existing growing stock inventory is also the stumpage factory, stock-supply responses tend to overshadow the other two supply responses. Stock supply is theoretically governed by the opportunity costs of holding the stock or inventory in relation to alternative rates of return. Short-run supply depends upon the rate of growth of the growing stock and, consequently, upon the cost of variable inputs that might be used during a timber rotation. Land is the main fixed input, and the short run may consequently span several decades. The long run corresponds to the period when all inputs are variable, including the decision whether to invest in timberland.

Although this outline of Duerr's (1960) timber supply theory is somewhat simplified, it still suggests the complexity of the dynamics of timber supply over time. With aggregation across many timber management situations, including various forest stand structures and conditions and diverse ownership classes with varying time frames and differing management perspectives, it becomes exceedingly difficult to distinguish between short run and long run for analytical purposes. The criterion of land as a fixed factor of production over a particular time period may apply to some owners but not to others. Thus the precise time period for which this factor remains fixed may be difficult to identify from an aggregate standpoint. Aggregate analysis in effect synthesizes a broad range of rotations which vary according to a wide variety of species and management conditions.

The concept of the short run as the transition period, during which the gradual depletion of old-growth timber and the merging of various management patterns results in a "steady state" forest situation (Lyon and Sedjo 1983), represents one conceptual approach to this problem. In this context, the long run represents harvest levels after the steady state has been achieved. Such estimates are of obvious importance with respect to the long-term status of the timber resource; however, this framework is difficult to apply in empirical supply analyses. Such an approach is addressed further in the following section on timber investment modeling. The present focus is upon the major techniques for modeling harvest flows, with less emphasis placed upon explicit criteria for long-term investment strategies.

Modeling of aggregate harvest flows has generally been addressed through two distinct analytical approaches: (1) simulation of harvest flows based upon historical relationships among current period harvest, stumpage prices, and some proxy for the opportunity costs of holding timber inventory (Adams et al. 1982); or (2) optimization techniques such as mathematical programming that schedule harvest flows so as to result in the maximization of some ownership objective.

Simulation models predict or display the consequences of a selected range of management alternatives; they generally provide information for selection of a desirable strategy by some method external to the simulation model. Duerr et al. (1975) classify optimization or "analytical" models as those that evaluate alternatives in order to find an optimum. The modifier "optimization" is used in place of Duerr et al.'s "analytical" to conform to popular usage of these terms in the literature.

Simulation techniques are often used in positive analyses, i.e., those in which responses of the timber resource to management in the future are projected as a likely continuation of response patterns that occurred in the past. Optimization techniques are generally associated with the normative modeling concept in which goals or objective functions with associated constraints are specified or prescribed. The distinction between simulation and optimization techniques is not always straightforward (Field 1978); some modeling approaches incorporate both as, for example, in the case of a mathematical programming technique utilized within the broader framework of a simulation model. Despite their simultaneous use for some modeling problems, simulation and optimization are discussed separately as the two most commonly used approaches for the modeling of harvest flows in aggregate timber supply analyses.

SIMULATION TECHNIQUES

Simulation has been used to represent the dynamic processes for a wide variety of situations in forest management (Bare 1971). In simulating large-scale forestry systems, key parameters and variables may be systematically varied to allow monitoring of system performance under a range of conditions. A dynamic simulation model is a representation of a system as it evolves over time. A deterministic simulation model does not contain variables, otherwise it is stochastic. Difficulties inherent in model validation, including statistical validation problems for stochastic simulation models, are discussed by Reynolds et al. (1981).

With respect to the modeling of aggregate harvest flows, simulation techniques have employed various assumptions regarding harvest trajectories. For example, baseline simulations have been obtained by assuming that harvest levels would increase until they equal annual growth (USDA Forest Service 1973). While earlier simulation efforts tended to focus upon biological and/or silvicultural aspects of timber management, the emphasis in simulating harvest flows appears to be shifting more toward incorporation of economic variables or proxies (Adams 1977, McKillop 1967, Robinson 1974). Simulation of the response of private timber harvest to changes in production costs and prices was used in the 1980 RPA Assessment (Mills and Alig 1979, Adams and Haynes 1980). Prior to this, harvest responses to economic variables had generally been determined in a judgmental fashion for major national timber assessments.

TAMM.—The Timber Assessment Market Model (TAMM), used in the 1980 RPA Assessment, is a compre-

hensive system of analytical techniques that models lumber, plywood, and stumpage markets in which supply and demand interact to determine equilibrium prices (Adams and Haynes 1980). Its stumpage supply modeling will be discussed as an example of simulating harvest flows using econometric techniques, which are statistical functions estimated by using economic precepts to guide model form.

TAMM's several analytical components estimate future prices, consumption, and production for softwood lumber and plywood, hardwood lumber, and both softwood and hardwood stumpage. Annual harvest flows are estimated by short-term supply functions, for which stumpage prices act as independent variables. These prices are obtained through a linkage of the stumpage and product markets; this is achieved by a complex simultaneous solution procedure for equations involving equilibrium prices and quantities (Adams and Haynes 1980). In effect, stumpage prices are estimated each model year for use in the short-run supply functions, and these supply functions shift over time as other independent variables change (e.g., timber inventory).

After the annual harvest flows are estimated in TAMM, they are then incorporated into the TRAS model (discussed previously) that has served as an inventory projection module for TAMM.[10] The TRAS model then calculates the timber inventory progression for the next annual cycle. The timber inventory at the end of that simulated cycle is then fed into the short-term supply functions as one determinant of the next year's harvest volumes. This cycle then repeats over the time period of analysis.

TAMM is one of the most comprehensive models available for projecting timber market activities, partly because of the attention given to the spatial juxtaposition of the various supply and demand regions and the linkage of the stumpage and product markets. Regional competitive advantages attributable to differences across supply regions in the cost of timber production are an example of economic behavior that can be simulated by such spatial modeling. Also, stumpage prices computed by a simple simultaneous equations procedure using the equilibrium values from the product market are used in the stumpage supply functions to estimate harvest volumes.

Domestic supply region boundaries used in TAMM modeling for the 1980 RPA Assessment (fig. 2) were largely dictated by availability of aggregate forest inventory data (Adams and Haynes 1980). Short-run supply or harvest functions used in the 1980 RPA Assessment were estimated for the eight domestic supply regions separately for softwood and hardwoods and four ownership categories. For example, eight supply functions were estimated for softwood and hardwood stumpage supplies of four owner classes in the South-Central region, one of the domestic supply regions.

[10]*The TRAS model itself has been modified to estimate harvest flows via stumpage-supply equations (Alig et al. 1982). Up to six independent variables can be specified for the equations (e.g., stumpage price) with the user providing both the appropriate variables and coefficients.*

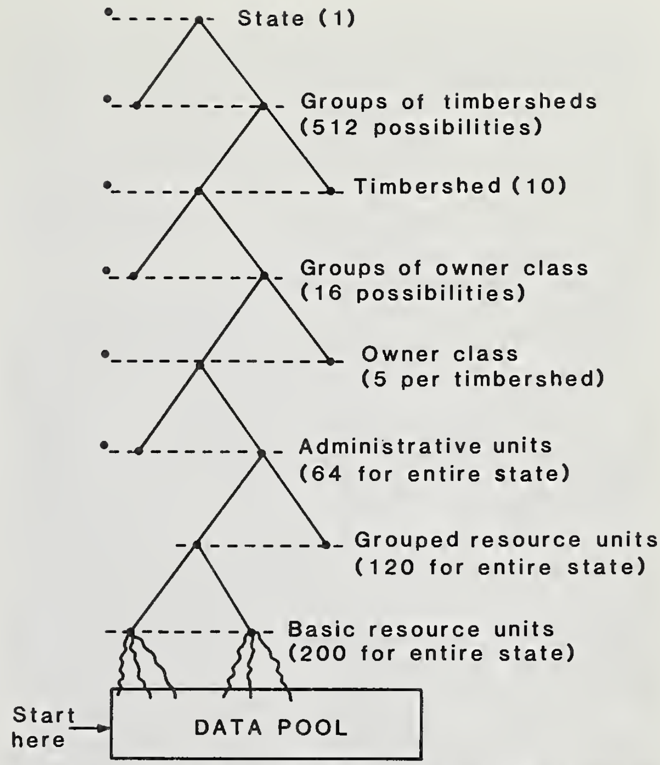


Figure 2.—Domestic timber supply regions used in the 1982 RPA Assessment (USDA Forest Service 1982).

The TAMM system has the flexibility for harvest flow estimations for more disaggregated supply regions, the major limitation being the existing levels of statistical reliability for collection and organization of data on timber inventories and owner supply behavior. This data limitation varies for different geographical areas, and augmenting data sources tends to be a long-term undertaking.

A typical (50-year) TAMM projection is relatively inexpensive because of TAMM's computerized nature, especially given the relatively low cost of long-term projections by the TRAS inventory projection module. The speed and low cost of TAMM projections make the system especially useful for sensitivity analyses. The influence of underlying assumptions can be tested through several projections by systematically varying input related to those assumptions.

The short-term harvest model embodied in TAMM is based on the following precepts: (1) private stumpage owners will vary harvest directly with stumpage price, and (2) private harvest will increase with available timber inventory levels (Adams and Haynes 1980). Adams and Haynes (1980) reported that TAMM explained historical harvest flow behavior reasonably well for the forest industry ownership in 1980 RPA Assessment analyses, but was generally not as successful in modeling private, nonindustrial harvest flows. TAMM's modeling of public stumpage supply behavior involves exogenously determined upper harvest bounds arising from allowable cut levels, established by legislated policies.

The modeling of private timber harvest by TAMM employs essentially the same functional forms for both

the industrial and nonindustrial owners. The relatively limited success in modeling nonindustrial timber harvest may be attributable to this parallel approach, which does not directly recognize the importance of nonmonetary forest returns to nonindustrial owners. Also, industry-related considerations, such as aspects of integration in industrial firms, are ignored by TAMM's short-term harvest modeling, which is based directly on price and timber inventory variables.

TAMM's difficulties in successfully modeling harvest behavior of the diverse class of nonindustrial, private landowners have been preceded by numerous studies that suggest few generalizations can be made regarding timber management patterns by nonindustrial landowners (e.g., Stoddard 1961, Sizemore 1973, McComb 1975, Clawson 1979). Binkley (1979, 1981) has proposed a model of timber harvest behavior of nonindustrial, private landowners that addresses multiple objectives of ownership, in the context of balancing harvest income and personal consumption of the forest's nontimber outputs. Binkley's theoretical model is based on utility maximization through consumption of (1) goods and services purchased through income from timber harvests and (2) goods based on nontimber outputs from the forest (e.g., recreation).

Data was not available for estimating the theoretical timber supply model outlined by Binkley (1981). For example, existing data for even the relatively small study area was inadequate for estimating technical tradeoffs between timber and nontimber outputs. A "stochastic utility" model of choice was developed using the available data, with a maximum likelihood logit estimator used to estimate the probability of harvest. Because probability of harvest was analyzed and other study conditions were variable, Binkley's (1981) empirical results cannot be directly compared to those for TAMM's modeling of private harvest behavior. However, results of Binkley's work indicate that probability of timber harvest is strongly influenced by stumpage price, while income is negatively related to harvest probability. Farmers are shown to be more likely to harvest timber than nonfarmers, and the farmer group also appears to be more price responsive.

OPTIMIZATION TECHNIQUES

Optimization models represent another class of quantitative analytical techniques frequently applied to the modeling of harvest flows. While simulation procedures are often used to develop a range of alternatives without specifying a single most desirable solution to the modeling problem, optimization techniques are designed to identify a particular "optimal" solution that satisfies a set of predetermined output criteria.

The specific aim of optimization is the maximization (or minimization) of the value of an objective function that incorporates the goal of the modeling effort (e.g., maximizing present net value or minimizing costs). For some problems, the model is allowed to arrive at an optimal solution in an unconstrained fashion; in many instances, however, a variety of constraints are specified as conditions for achievement of the optimal solution. Optimization models for timber management have generally been of this latter variety. Variables in the objective function and constraint equations, whose value in the optimal solution are to be determined, are referred to as decision variables.

Optimization techniques applied to estimate harvest flows in timber supply analyses have used a variety of biological, economic, and other specified objective function criteria, as well as a wide range of model constraints (e.g., Navon 1971). Johnson and Scheurman (1977), Bell (1977), Field (1978), Marty (1979), and Hann and Brodie (1980) review optimization tools for harvest estimation in even-aged forests, and Hann and Bare (1979) discuss techniques for uneven-aged cases. Optimization techniques evaluate harvest decisions as part of a total timber management package that includes other management practices; these management alternatives are prespecified external to the model. This important interdependency of the management variables in terms of joint optimization will be discussed further in the following section.

Among these optimization approaches, linear programming (LP) has been utilized most frequently for the modeling of harvest flows. This in part reflects the ability of LP to address large-scale modeling problems and its degree of computational efficiency relative to other optimization procedures. A primary assumption of any LP analysis is that the problem being modeled is capable of being formulated in such a way that an optimal solution to that problem may be found. A recent application of LP utilized by the USDA Forest Service for National Forest lands is discussed below as an example of the optimization framework for modeling harvest flows.

FORPLAN.—The Forest Planning (FORPLAN) model is a linear programming (LP) package that has been applied to the complex optimization problems associated with National Forest planning mandated by the National Forest Management Act of 1976 (Johnson et al. 1980). FORPLAN is actually a software package that serves as a linear programming matrix generator, an interface to the UNIVAC 1100 FMPS LP solution algorithm, and a report writer for describing the LP solution. The LP matrix generator converts data input into a matrix of rows and columns. This matrix is then used in the simultaneous solution of land allocation, land management or investment scheduling activities, and output mix. The report writer can produce final output in a variety of specified formats. FORPLAN essentially evolved from a timber management model known as the Multiple Use-Sustained Yield Calculator (MUSYC) and retains emphasis on timber analysis capabilities; however, prescriptions and output scheduling for a variety of resources can be examined as well, if relevant biological and economic information is available.

FORPLAN can construct an LP based on either Model I or Model II structures for timber harvest analysis (Johnson and Schuerman 1977). Basically, these two model structures differ in the manner in which they define timber management variables and handle multiple harvests within the planning horizon. In the Model I

structure, a variety of management activities can occur on a particular land area over the entire planning horizon, with the specified area retaining its identity throughout the process. In the Model II approach, individual parcels of land are not kept intact through time because harvested acres are recombined into new management units. Model I is more effective in keeping track of location on the ground, while Model II is more conducive to minimizing model size. In terms of earlier timber management models, FORPLAN can employ the Model I structure of the Timber Resources Allocation Model (Timber RAM) developed by Navon (1971) or the Model II structure of the MUSYC model noted above.

Joyce et al. (1983) review the history and foundations of linear programming applications in the natural resources area, including the use of FORPLAN as a multiresource analysis tool for relatively small areas. The timber harvest analysis capabilities of FORPLAN are similar to other LP models used for optimization analyses (e.g., Ware and Clutter 1971), and they are discussed only briefly in this report. Johnson and Schuerman (1977) compare different types of LP models that utilize Model I or Model II frameworks, discuss the different solution techniques that have been applied, and also review quadratic versions of Model I and Model II (e.g., Walker 1971).

Basically, an LP model such as FORPLAN can maximize or minimize a linear objective function subject to linear constraints. Ten different possible forms of objective functions for FORPLAN are listed by Joyce et al. (1983). FORPLAN can also generate a piecewise approximated downward-sloping demand curve for timber. Fixed prices are assumed for all other outputs. At this time, costs can be assigned per acre for timber-related management prescriptions, and per unit output for all outputs (including timber). It is anticipated that the capability to assign costs per acre for all management prescriptions will soon be available in FORPLAN. An option to include fixed costs is also available in the model.

Output constraints or output targets are an important part of the LP formulation within FORPLAN. These targets set minimum or maximum levels of outputs to be obtained in the LP solution and actually drive the model in some instances. Inclusion of certain specific targets is directly mandated by the NFMA regulations. The fifteen kinds of tables and graphs which constitute the outputs of the FORPLAN model include the objective function value, constraint output, land allocation areas, harvest reports (area and volume), economic reports (costs, prices, revenues, present net worth, present net benefit), regeneration levels, and cultural treatments (Johnson et al. 1980).

FORPLAN allows considerable flexibility in the user designation of analysis areas and management prescriptions. Analysis areas are assumed to respond the same way to a given management prescription, regardless of where they occur. Analysis areas are defined by six levels of identification: levels 1-3, user-specified land characteristics (60 categories for each level); level 4, working groups (9 categories); level 5, land classes (15 categories); level 6, existing vegetation classes (60 categories). Every alternative management prescription specified in FORPLAN must apply to a given analysis area. In addition, alternative prescriptions can be included to apply to the regeneration classes created by prescriptions with harvest practices.

Production coefficients associated with specific treatments and land types are input into the model as yield tables. They generally represent the number of units per acre of output resulting from a given treatment applied to a given analysis area. Prices and costs are entered in the same manner as the yield tables noted above. The time frame that applies to management prescriptions as well as to resultant outputs is quite variable; it may consist of up to 30 time periods of from 1 to 20 years each.

FORPLAN model formulations may involve constraints relating to any or all of the following: area and volume control, harvest flow (e.g., nondeclining yield), ending inventory, management emphasis and intensity, and cultural treatments. These constraints may be represented by numerous configurations, and generalizations are inappropriate in this report. For example, the determination of which management alternative to examine within the FORPLAN model, and the derivation of the associated biological response (e.g., yield tables) are for the most part forest-specific.

Apple (1982) surveyed FORPLAN users in 7 of the 9 USDA Forest Service regions regarding the utility of FORPLAN for planning activities on National Forest lands. Most respondents, who consisted primarily of forest planners and operations research analysts, indicated that between one and twelve initial model runs were required to obtain a usable solution. Approximately 60% of respondents were utilizing Model I for analytical runs; the remaining 40% were employing Model II. Model I was regarded as less costly and easier to track, while Model II was considered to be better suited for forest management data and a more flexible analytical tool.

Among some of the unexpected benefits arising from the use of FORPLAN, planners and analysts felt that it provided a better evaluation of inventory, an increased understanding of the role of economics in forest management, better coordination of management functions, and a better overall understanding of the forest management system. Problems listed most frequently included the need for more direction in model use, the lack of or poor quality of input data, and lack of time for analysis, particularly with respect to the performance of sensitivity analysis for model results. Users indicated that the major areas of information needs included economic data and yield data for timber and other resources.

Although the FORPLAN model has primarily been applied at the individual National Forest level, the relationship of forest-level FORPLAN implementation, as well as other optimization techniques, to aggregate timber supply analysis is of major importance within the context of this report. Aggregate timber supply analysis for national assessments necessarily involves a critical linkage of potential harvest flows from public and private sources; however, these two sources are typically modeled with varying detail. Public timber harvest flows

in the most recent national timber assessment were essentially exogenous estimates, while private harvests were estimated using TAMM's simulation modeling. Questions have arisen regarding the possible expanded use of FORPLAN output from forest-level modeling for national assessments, or use of a modeling framework similar to FORPLAN's but at a broader regional level.

These concerns regarding the potential applicability of optimization techniques for modeling public harvest flows at aggregate levels (e.g., National Forest region) are also relevant to the modeling of aggregate private harvest flows in some regions. The multilevel or hierarchical decision problem of different planning levels (e.g., national, regional, and Forest/local) is difficult to solve because of the need to recognize (1) that variables under control of policy makers are distinct from those under control of the micro unit or behavioral decision maker and (2) conflicting objective functions may exist for different owners throughout the hierarchy (Candler et al. 1981). The goals of economic units can also often be stated more explicitly and unambiguously at the micro level than at the macro level. Specification of appropriate or realistic objective functions and constraints at aggregate levels for the various owner classes could be difficult tasks, particularly for the diverse nonindustrial class. Aggregation across such diverse owner and timber resource conditions may also lead to relatively large model size and cost if needed modeling detail is to be achieved (Ashton et al. 1980). Little has been reported in the literature regarding the feasibility of modeling aggregate timber harvest flows solely within an optimization framework; however, mathematical programming has been utilized in somewhat analogous roles to model agricultural supply activities (e.g., Meister and Nicol 1975).

Another potential difficulty with respect to expanded use of optimization modeling involves questions regarding computational efficiency that stem from the necessity of arriving at a single optimal level in order to satisfy the production of a desired output (e.g., timber). As an alternative to addressing the large computational requirements of the LP process, Hoganson (1981) describes a method whereby the LP problem is formulated as a simulation. This simulation model is driven by shadow prices (dual variables in an LP formulation) and the iterative process continues until harvest levels are driven to a level close to that specified in the regional LP problem. The technique has the potential for significant cost reductions in the analysis of large LP problems.

OTHER APPROACHES

Goal programming (GP) is a particular form of LP used to find a solution to a resource allocation problem involving several objectives, subject to a set of linear constraints. Depending on the type of formulation, all goals may be considered simultaneously in a composite (and single) objective function or sequentially in a series of objective functions (Bell 1976, Field 1978, Field et al. 1980). The choice variables are deviational ones—showing overachievement or underachievement of the specified goal levels of output. As with FORPLAN, most GP models have been applied to relatively small areas. Schuler et al. (1977) suggest that the largest application problem involves determination of the technical coefficients (i.e., the amount of output that can be anticipated from a given input).

Another approach based on mathematical programming is Berck's (1979) empirically based model of long-run timber supply behavior. Berck tested the hypothesis that private owners cut their timber at a rate exceeding an optimal one based on alternative rates of returns. This analysis involved estimating the rate of time preference indicated by the interest or discount rate implied in historical management of Douglas-fir by private landowners, assuming they maximized present value of profits. Berck found that cutting rates for private landowners indicated they were discounting the future at a rate much lower than the rate of return available for other private investments and much lower than that proposed by Arrow (1976) as a social discount rate. Berck's assumption of rational price expectations by private landowners in order to maximize profits over a 175-year period implies knowledge and behavior that may not be representative of many private forest land owners. Nontimber benefits from the private forests were not included in this modeling of private forest owner behavior.

TREES.—An example of a comprehensive approach to modeling aggregate harvest flows is the Timber Resources Economic Estimation System (TREES) (Johnson et al. 1975, Tedder et al. 1980) model. This model contains a number of harvest estimation options, including variable harvest scheduling methods that use a multiple iteration binary search. The aggregation scheme of the TREES model is noteworthy for its sophistication and flexibility.

The TREES model was originally developed for a comprehensive study of future timber supply for the state of Oregon (Beuter et al. 1976). The model projects different harvest levels in response to varying assumptions about land use changes, growth rates, trends in silvicultural intensity, harvest control policies, and utilization efficiencies. TREES is capable of (1) projecting timber volumes resulting from either natural stand development or in response to specified treatment activities, (2) simulating harvests at numerous administrative levels, and (3) considering multiple stocking levels in inventory projections. The TREES model can also project timber inventories for both even-aged and uneven-aged forest structures. The key to these capabilities is the availability of yield tables. TREES does not provide such tables; it uses them to make timber inventory projections. Input to the TREES model includes base growth and yield information via growth functions, tables, or a combination of the two. These are keyed according to forest type, site, and acreage of each class by owner and administrative unit.

Seven harvest scheduling options allow the user to simulate harvest levels under current public and private management practices and to simulate new harvest schedules to evaluate policy alternatives. These harvest

schedules are developed through either single (fixed harvest schedule) or multiple (variable harvest schedule) iterative computer runs. The three fixed methods do not use an iterative search to find the harvest level, so no optimization occurs (Schmidt and Tedder 1980).

The three fixed methods can schedule harvest in accordance with the following rules:

1. Area control: Number of acres to be harvested is determined by dividing total available acres by a prespecified rotation length.
2. Percent of inventory: A proportion (fixed or variable) of the available inventory is to be harvested each period according to the harvest priority chosen (e.g., oldest age first).
3. Absolute amount: A specified timber volume, selected on the basis of the harvest priority rule, is to be harvested each period.

The four variable or multiple iteration procedures embody principles of several other harvest scheduling models. In development of these timber flows, a binary search technique estimates the following:

1. An even flow of timber volume sustainable over an entire specified projection interval, similar to the approach used in the SIMAC model (Sassaman et al. 1972). Alternatively, an even flow of timber volume is estimated for each harvest period within the projection interval. When this technique is used, the allowable cut is recalculated at the beginning of each harvest period throughout the entire projection period. This approach embodies the ideas of the SORAC model developed by Chappelle and Sassaman (1968).
2. An even-flow as in item 1, except that the variable of interest is a linear function of volume instead of volume itself. Such volume-dependent variables include employment or gross revenue.
3. Harvest rates based on the economic criterion of present net worth (PNW) in a constrained maximization framework. This approach is similar to the ECHO model proposed by Walker (1971), where the volume harvested is determined for a timberland owner facing a negatively sloping demand curve that reflects quantity and price interactions and market power.
4. Harvest schedules to maximize present net benefit (PNB), which is the net discounted difference between a measure of the consumer's "willingness to pay" and total cost. This harvest scheduling method is analogous to item 3, except that it maximizes PNB rather than PNW, and the former is relatively more difficult to estimate. The output projections are given by timbershed and decade for timber volume and growth, volume and value of harvests, volume and value by products, and payments in lieu of taxes.

One of the strengths of the TREES model is its elaborate control structure when it is used to aggregate the timber harvests. This control structure organizes resource units in such a way that the model can keep separate and monitor a large number of resource units (fig. 3). The hierarchical aggregation scheme of TREES can currently aggregate information for up to eight different levels.

The basic resource unit for TREES is the smallest piece of land for which a beginning timber inventory may be entered. Examples of resource units from the Oregon study are even-aged units represented by volume per acre by age class, site class, and species for western Oregon, and uneven-aged units represented by number of trees per acre by diameter class in eastern Oregon. The next level of aggregation is the grouped resource unit, a collection of basic resource units all possessing a similar resource quality (e.g., a group of forest stands of single species and site class and all being managed under the same harvest method). The grouped resource units or management units are the lowest level at which timber harvests and projections are estimated.

Grouped resource units can be combined to form administrative units. Administrative units are sensitive to institutional constraints and closely follow the level at which federal harvests are regulated. Harvests are generally calculated at this level, and each projection has its own assumptions about land use changes, management intensities, and harvest control procedures.

Administrative units may be combined within an owner class, and owner classes can be grouped within a timbershed. The timbersheds can then be aggregated into groups within a state or a multistate region. For the Oregon study, the state was divided into a collection of timbersheds that were defined as the geographic area from which the primary needs of a wood processing center were supplied. A major advantage of the flexible aggregation scheme of the TREES model is that harvest quantities can be determined at any level from the grouped resource unit up to the state level.

The TREES model was also utilized in a Pacific Northwest Regional Commission Study of timber supply in Washington, Oregon, and Idaho (Rahm 1981). In the baseline analysis, the harvests of public sector owners are assumed to continue along the current planned path through the next century. Private timber owners are assumed to respond fully to market forces, harvesting timber at a rate that maximizes the present net value of their timber income stream in every decade for the next 100 years. In an "optimizing simulation," the TREES model selects harvest schedules in conjunction with downward-sloping demand curves (net of planned public harvest) for delivered logs in two subregions. The assumed objective function is the maximization of present net benefit; harvests are selected in each time period so that the discounted net revenue from the last (marginal) unit of wood harvested is just equal to what that unit would yield if allowed to grow and be harvested in the next time period.

Because the flow of delivered logs is the focus of this equilibrium analysis, the costs of removing and hauling the timber determine the corresponding stumpage sources. Per unit costs by age class for felling, bucking, skidding, and hauling are required for final harvests and thinnings. Price adjustment factors are utilized to

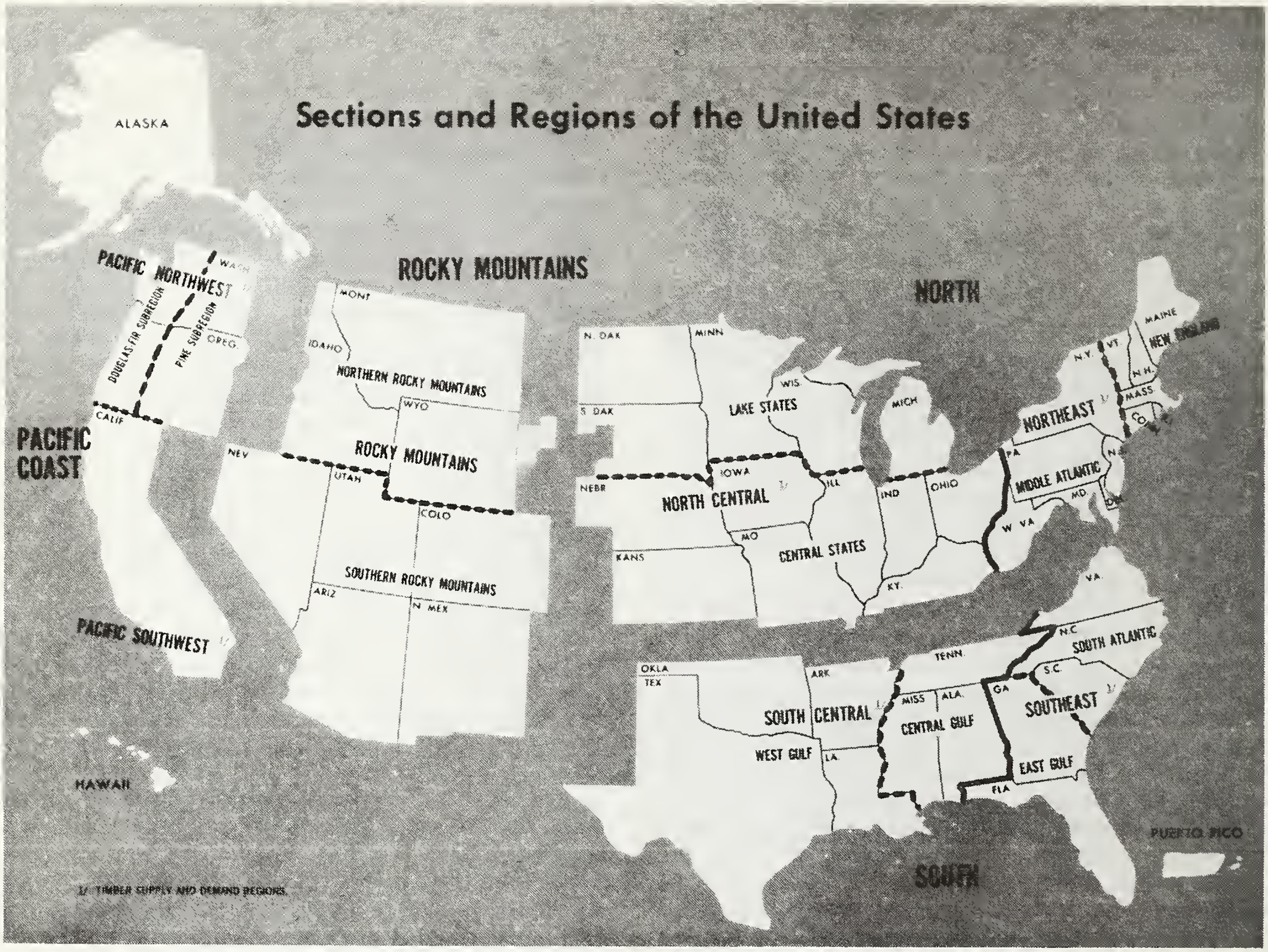


Figure 3.—Control structure of the TREES model used in Oregon study to aggregate timber supply information (adapted from Johnson et al. 1975).

reflect the differing values of logs harvested from stands of different ages.

Following this study, Rahm (1981) pointed out the following model limitations with regard to timber inventory projection capabilities of the TREES model: (a) certain combinations of timber management activities cannot be simulated, necessitating the use of broad average management practices; (b) the time path of changes in timber management intensity seems unrealistic because the proportion of total acres in a class rather than the proportion harvested is shifted after harvest; (c) a management intensity change (e.g., fertilization in middle-aged natural stands) cannot begin until acres are harvested; and (d) acres shifted from nontimber management to timber management are assumed to have the same average age structure and volume per acre as acres already in the management base.

While the TREES model considers the cost of removing timber from the stump and transporting it to market, Rahm (1981) indicates that the model does not properly specify the changes in costs associated with shifts in the geographic concentration of harvests over time. The model selects timber for harvest in areas that yield the highest average net value based on the harvest costs. This constrains timber harvests solely to a subset of analysis areas (i.e., grouped resource units) in a stepwise manner, rather than having them more widely distributed geographically. Because of this inter-subregional harvest optimization procedure, the resulting harvest flows may not necessarily be a realistic indicator of the actual location of future timber harvests within a region.

Rahm (1981) further points out that the TREES model tends to be expensive to operate because its "all-purpose" orientation results in a size and complexity of the model that tend to make individual runs costly. Also, because it is an extremely open-ended tool, a considerable amount of time is required for the user to become familiar with its operation. However, once basic model runs are set up, revisions can be made relatively quickly and large data sets can be accommodated satisfactorily.

The TREES model also does not necessarily calculate economic optima, but produces approximations because of assumptions such as those listed by Schmidt and Tedder (1980). For example, one assumption is equivalent to ignoring the opportunity cost of delaying future harvest.

Rahm (1981) suggests that such deviations from economic optima may not be significantin some applications, especially in view of the degree of error inherent in some data that is used.

INTEGRATION OF HARVEST FLOWS AND TIMBER INVENTORY PROJECTION MODELING

Linkage of the four analysis components in aggregate timber supply studies has been improved in recent years, particularly with respect to interactions between biological and economic processes. However, the modeling of harvest flows and investment has seldom been as detailed as that for timber growth in past studies. Future harvest patterns were sometimes estimated on the basis of simplified assumptions or scenarios, with no explicit consideration given to linkages with trends in important economic variables (e.g., prices). Despite recent efforts to devote more attention to economic processes, questions still remain regarding the appropriate balance of modeling detail for biological and economic components in aggregate timber supply studies.

While more effective integration of biological and economic models has slowly occurred, the flexibility of such analytical packages for examining timber supply policy questions is still rather limited. For example, the TAMM harvest flow modeling discussed previously relied on timber inventory projections by the TRAS model, which is relatively inflexible in its capabilities to simulate timber management alternatives. This rigidity in the biological simulation component diminishes the usefulness of the overall analytical package for timber supply analysis.

Models that are independently developed and later linked together often require major adjustments in order to permit efficient and effective joint operation. A major problem may occur when biological and economic models must interface at a common level of aggregation. For example, the integrity of TRAS's biological modeling may be diminished if it is applied to large geographical regions which serve as the bases for harvest flow equations or other economic modeling. Aggregation across many silvicultural conditions, such as site classes, stocking levels, and stand structures, may more adversely impact model validity for the biological modeling components than for those involved with modeling economic processes.

SUMMARY

The TAMM model (Adams and Haynes 1980) represents the most comprehensive approach for integrating short-run private harvest behavior based on historical patterns with long-term timber management strategies. Econometrically derived short-run harvest flow equations are shifted through time in a TAMM simulation, as in the 1980 RPA Assessment. Stumpage price and timber inventory levels are the independent variables in the harvest flow equations, which are somewhat ad hoc in nature. The TAMM approach has the strongest explanatory power with regard to forest industry behavior, but it generally encounters major difficulties in attempting to explain the harvesting behavior of nonindustrial, private landowners. Other empirical studies of nonindustrial harvesting behavior include Binkley's (1981) dichotomous procedure for estimating the probability of harvest in a certain year. Although substantial data problems were encountered, stumpage prices were shown to strongly influence the probability of harvest.

The Forest Planning (FORPLAN) model (Johnson et al. 1980) represents the application of optimization techniques to the modeling of harvest flows. This linear programming (LP) model evolved from previous LP approaches for timber harvest scheduling, but FORPLAN differs from its predecessors in its multiresource dimensions. Applicability of the FORPLAN model and other optimization approaches to the modeling of aggregate harvest flows is hindered in part by difficulties in specifying objective functions and constraint equations for such analyses. Other mathematical programming approaches include Berck's (1979) empirically based model of long-term timber harvesting patterns. This modeling of the intertemporal dependency of harvest and management decisions involves estimation of private landowner rate-of-time preference as a behavioral parameter.

The Timber Resources Economic Estimation System (TREES) (Johnson et al. 1975, Tedder et al. 1980) is a relatively elaborate harvest scheduling model that has seven harvest scheduling options. The variable harvest scheduling methods (e.g., present net worth algorithm) use a multiple iteration binary search, and several options can be applied to either even-aged or uneven-aged stands. TREE's aggregation scheme has considerable potential for expanded adoption in aggregate timber supply studies, as it utilizes a comprehensive, hierarchial control structure. The aggregation control structure allows harvest quantities to be determined at any level from a grouping of basic resource units up to the state level.

4. TIMBER INVESTMENTS

Investments to enhance the productive capacity of forests involve utilization of inputs which influence the growth of the inventory over time and future harvest levels. The process of timber production may require input expenditures (e.g., artificial regeneration) well in advance of when the effects of those inputs are realized (i.e., gestation period). Capital theory deals with the time path of capital accumulation, and harvest flows discussed in the preceding section are part of the capital formation process in forestry, representing disinvestment or liquidation of accumulated timber capital stocks.

Although timber investments are important for long-run timber supply, analyses of aggregate timber investment patterns have been rather limited. Decisions to

undertake intertemporally linked timber investments such as planting, thinning, or fertilization theoretically depend on anticipated physical yields, opportunity costs of such investments, and stumpage prices. However, with the diversity of owner objectives (even within owner classes) and the widespread deficiencies in technical production and behavioral data, realistic modeling of long-term timber management behavior remains one of the more difficult tasks facing timber supply analysts.

The theory of aggregate forest investment is not well developed, and almost all applied timber investment analyses have been conducted at the stand level. While there has been considerable statistical testing of aggregate investment theories with regard to the general economy, results from these efforts have generally not been very satisfactory and no widely accepted theory of investment exists (Ackley 1978, Clark 1979).

Aggregate timber supply analyses have employed a variety of assumptions and approaches for modeling timber investment patterns in long-run supply studies. The importance of transitional, as opposed to steady-state, aspects of aggregate timber supply has been emphasized to different degrees in various studies of timber supply. Transitional patterns involve states of disequilibrium and change in the stumpage sector. The disequilibrium pertains to both stock variables that have no time dimension (e.g., timber inventory), flow variables (e.g., harvest) that are time dependent, and associated ratios of the two. Movements in the "system" comprising the timber economy may result in an essentially continual disequilibrium over time because of continuous changes in external circumstances such as productive techniques, population, consumer preferences, and government actions.

Conversely, some studies emphasize steady-state behavior for at least some aspects of a timber supply system over time. Examples are long-run harvest levels formulated according to constant economic parameters over time, or repetitive cycles of identical forest management strategies on land assumed to be initially bare. Steady-state conditions imply that relevant variables all grow at an identical rate, which is a generalization of the concept of the stationary state for which the relevant variables all remain constant (i.e., grow at a zero rate). The stationary equilibrium state is one in which the system operates in a similar manner year after year unless it is disturbed by some outside force. Furthermore, in steady-state analysis production functions or technology are assumed to be invariant over time. Some analyses may also assume asymptotic behavior in relation to inherent limits for the system.

The theory of long-term timber investment based primarily on steady-state or static profit maximization principles is discussed by Hyde (1980) and Jackson (1980). Hyde applies analytical tools based on economic efficiency norms in a Pacific Northwest timber supply analysis, and devotes special attention to public forest land activities. As previously mentioned, Hyde also gives an extended theoretical treatment of the economically efficient allocation of forest land among market and nonmarket uses, which encapsulate long-term investment strategies.

Hyde's static approach focuses on the economic efficiency of public land allocation and management, and he concludes that increased levels of both timber and nontimber outputs are possible. This approach is similar to that of Clawson and Hyde (1976) and it does not address some timber market ramifications of increased public supply. These include the responses of private producers to any changes in public supply behavior and interregional linkages of product and stumpage markets. The important question in the Pacific Northwest with respect to old-growth timber and conversion policies is handled in a very general manner, with no examination of dynamic-adjustment paths. Feasibility of attaining a long-run annual harvest level that would not significantly increase relative stumpage prices is investigated, rather than the actual path of an optimal conversion policy and the resulting market implications.

Jackson (1980) orients his theoretical discussion toward the microeconomic framework of the private timber firm, developing a theory of timber supply under conditions in which production is time dependent. For example, under a particular set of assumptions, regeneration inputs and rotation ages as decision variables are shown to be substitutes, rather than complements, in the productive relationships. These types of timber production relations are important for long-term timber management analysis, and Jackson also points out information gaps that exist in the area of timber production processes.

Two different types of timber investment analysis techniques are discussed next which address dynamic aspects of long-term timber supplies—optimal control theory and analysis of investment opportunities in an overall simulation framework. These two analytical systems reflect a contrast between theoretical and applied timber investment modeling. They also focus on different aspects of the multidimensional timber supply question, particularly the distinction between short-term transitional supply responses and long-run stationary state behavior.

OPTIMAL CONTROL THEORY

Optimal control models describe the evolvement of a system over time and determine optimal levels of decision variables over time, relying on the maximum principle of optimality (Clark 1976). State equations describe the evolution of the system from an initial state, resulting from the application of a given control. The fundamental problem in optimal control theory is to determine a feasible control that maximizes an objective functional (i.e., an optimal control) in order to determine an optimal path or trajectory through time. The maximum principle gives certain necessary conditions that must be satisfied by an optimal control. Techniques of optimal control theory can handle nonlinear optimization problems and inequality constraints.

SPOC.—The Supply Potential Optimal Control (SPOC) model is an optimal control theory model for estimating

regional long-term supply of timber (Lyon and Sedjo 1983). A recent application using hypothetical timber supply data addresses the constrained maximization problem of optimal timber harvesting and forest investments or management practices. A long-run supply potential based on economic considerations is investigated, using an endogenous determination of the economically optimal intertemporal levels of silvicultural inputs. Optimal rate of drawdown or conversion of existing old-growth stands is examined, and output levels are projected for steady-state conditions after the transition. Timber strategies that are examined pertain to the rate at which the timber stock is changed by rates of reforestation and afforestation, and also by other management that alters biological growth rates.

In the SPOC model, composition of the long-run supply curve changes as the transition progresses from short-run fixed timber stocks to those in the long run, where the stock is variable. Once the transition is complete, a steady-state forest situation ensues. The length of the transition period is specified beforehand, and the SPOC model does not solve for it using a simultaneous optimization approach.

Optimal long-term timber supply potential is analyzed by the SPOC model as a discrete optimal control theory problem, with the large multiperiod problem decomposed into a series of smaller, single time period problems. The model optimizes the level of management input and rotation length, and provides projections of regeneration, growth, and harvest for each class of forest lands. Important real world considerations such as ownership patterns and institutional constraints are considered to be noneconomic factors and are not addressed, given that the intent of the SPOC modeling is to focus on basic long-term biological and economic processes.

Biological variables are embodied in production functions in the SPOC model; initial conditions and "laws of motion" comprise necessary background information. Initial conditions include such items as acres of forest by age group and land class and composite regeneration input for each of the acres. Laws of motion are rules that govern the system, including those that redefine acres of trees in an age group and the regeneration input from one year to the next.

Economic optimization by the SPOC model proceeds by land class, with optimal regeneration input and rotation period calculated for the stationary state and then for the desired transition period. Control variables in the transition period phase are harvest levels and the level of regeneration input in each year by land class. The stationary state variables are the acres of trees by age and land class and the associated regeneration input for each of those acres. The model maximizes the discounted present value of the intertemporal net sum of producer and consumer surplus (net surplus) subject to an appropriate set of technological and cost constraints, with the optimal control theory algorithm used as the solution technique.

Optimal control variables are solved for by the use of gradient vector techniques, in which time paths are based on the direction of maximum ascent of the present value of a "net surplus hill." Total costs are the sum of regeneration and harvesting costs. Regeneration input expenditures depend on the acres harvested, with no assumed regeneration lag. Harvesting involves a fixed entry cost per acre and a variable cost that depends upon total volume harvested.

Values for the objective function represent present value of the net surplus stream, which is maximized subject to a set of constraints. These are constraints on the values of the control variables and the laws of the motion of the system, e.g., the portion of acres harvested has to be nonnegative and less than or equal to one. Constrained maximization of the objective function proceeds by decomposing the overall problem into a series of subproblems (i.e., maximum principle). Each iteration in the gradient method moves the time path or trajectory of the variables closer to the optimum.

The gradient vector which determines the direction of maximum ascent of the net surplus hill is the derivative of the objective function with respect to the control variables. Thus, it is the vector of shadow prices or values of the control variables, i.e., rate of change in the objective function per unit change in a control variable. These shadow prices indicate whether an increase in a particular control variable will increase the value of the objective function.

Applications of the SPOC models have used hypothetical data to project the economically optimum time path of prices and harvest volumes. Variants of the model can be applied to examine regions where data are available; however, data availability in the short term may be a major constraint on actual application and testing of the embodied techniques. Lynn and Sedjo (1983) propose that several regions could be incorporated, if data were available, by introducing each region as a separate land class or groups of land classes.

The potential usefulness of optimal control models in aggregate timber supply analyses is difficult to evaluate because it is a relatively new analytical tool. Zilberman (1982) suggests that optimal control analysis is a powerful tool which expands the range of issues that agricultural economists can deal with, as well as increasing their effectiveness. Wide-scale application of this approach may be impractical at present, however, because of the data requirements for solving dynamic optimization problems. Optimal control models with stochastic elements are much more complex than deterministic ones (e.g., Lyon and Sedjo 1983), including the most advanced technique, named adaptive control, that takes into account the expected gains from future learning in determining optimal control levels (Zilberman 1982).

RELATED APPROACHES

Cohan (1982) also utilized optimal control theory in constructing a detailed theoretical model of private sector forest management and timber supply. This long-run model determines optimal investments in timber man-

agement activities (e.g., fertilization), the timing and levels of harvest, and cost-minimizing harvest patterns. This dynamic model of forest management and timber supply is based on the assumption of profit maximizing behavior and is linked to a set of simpler models of mills, market interactions, and forest products demand. This network is designed to be a flexible system of market equilibrium models of the timber industry. This optimal control model has also not been applied extensively to date.

Mathematical programming techniques, including linear programming, goal programming, dynamic programming, integer and mixed integer programming, and quadratic programming, have also been used in timber investment analyses (Bare 1971, Martin and Sendak 1973). They are designed to select an optimal solution for a set of variables, often called activities. The optimal outcome is the numerical maximum or minimum of some specified performance criterion or objective function.

Dynamic programming (DP) has been used at the stand level to solve for the simultaneous determination of rotation and intermediate treatments in timber investment analyses. The DP algorithm requires discrete time and stocking interval specification, in contrast to the use of continuous time or removal variables in some optimal control theory formulations. DP and its applications to forestry are discussed by Schreuder (1968) and Brodie et al. (1978). One of the earliest reported applications for analyzing multistage, sequential decisionmaking regarding timber investment paths was that of Amidon and Akin (1968). This is essentially a recasting of Chappelle and Nelson's (1964) marginal analysis of optimal loblolly pine stocking levels at the stand level (based on an iterative computer program) into a dynamic programming mode. More recent applications of DP are discussed by Brodie et al. (1978), Brodie and Kao (1979), Kao and Brodie (1979), Martin and Ek (1981), and Riitters et al. (1982).

ANALYSIS OF INVESTMENT OPPORTUNITIES

TAMM.—The TAMM model (Adams and Haynes 1980) examined in the previous section represents the applied state of the art in aggregate timber investment modeling. TAMM embodies a unique interregional linkage among long-term management or investment modeling, short-term supply (harvest) estimation, and stumpage price determination. Investment modeling by TAMM is based on normative analyses that involve economic maximization calculations, but are later linked to positive harvest flows modeling. Application of TAMM timber-investment modeling in an aggregate timber-supply analysis is discussed by Adams et al. (1982).

The TAMM investment model is an iterative process that determines the level of timber investment based on present net worth calculations and the associated extent of growth augmentation in the TRAS timber inventory projection module (Adams et al. 1982). Stumpage price impacts of those added investments are then simulated, with only a part of the eligible investments undertaken each year. A new stumpage price is then fed back to recalculate the level of timber investment and growth augmentation. This entire cycle is repeated until there is a sufficient convergence of stumpage price. Convergence of price implies that price expectations at time of investment are actually realized when the investment matures and the resulting stumpage increment is marketed (i.e., perfect price expectations).

Forest investments influence short-term supply relations in the TAMM model, changing future harvests and stumpage prices. Owners are assumed to recognize this interrelation between investments and future prices, including all future investments, under the assumption of perfect price expectations. Constraints on rates of investments are imposed by limited availability of capital, with economic gain from timber production assumed to be the sole objective of all owners.

Constant discount or interest rates are used in the timber investment analysis in TAMM to account for opportunity costs of investing in timber growing; however, forestry is the only major land use considered, and changing relative prices for products from other uses of the land are not considered. Timber growers are assumed to have perfect price expectations (i.e., expected prices are actually realized when investments mature several decades into the future) and to have the sole objective of maximizing their financial position. Timber production yields and returns are also usually modeled under certainty, with no explicit allowance for land use shifts or productivity setbacks.

Reasonableness of assumptions such as economic rationality and perfect price expectations by private owners are difficult to evaluate fully because of the data deficiencies surrounding actual private timber investment behavior. Assuming profit maximization as the sole objective of the selection and implementation of timber management practices on private lands ignores other owner objectives and concerns for amenity and other nonmarket forest outputs. The annual rate at which admissible investments are undertaken is arbitrary because little is known regarding actual financial and other constraints that influence private timber investment behavior.[7]

The TAMM investment analysis techniques were first employed in the 1980 RPA Assessment (USDA Forest Service 1982). The development of the SPATS model for the South has also expanded the analytical capability of the TAMM system in terms of examining the timber supply impacts from government expenditures to subsidize timber management on nonindustrial lands (Brooks 1983b). Continuing research on the TAMM analysis framework includes development of a Timber Resource Inventory Model (TRIM) for major timber supply regions that incorporates modeling of management intensification practices. The general format of the TRIM model is based on attributes of the aggregation structure of the TREES model (Tedder et al. 1980) discussed earlier and also on TAMM's investment modeling (Tedder 1983).

Modeling of management intensification for even-aged stands by the TRIM model relies on the yield table

projection approach. This age class approach, similar to that for the TREES model, allows the timber inventory to be segregated so that management practices can be tailored according to site, species, stocking levels, and age. This is more specific than the 1980 TAMM approach, which relied on an augmented TRAS model (Barber 1980), where all acres in an aggregate were assumed to receive the same basic package of management practices over time.

The economic process that drives the TRIM investment model is based on perfect price expectations, as in the 1980 TAMM approach. If the estimated rate of return is equal to or exceeds a specified alternative rate of return, investments are implemented on a perpetual rotation basis. Annual prices used in the calculations of soil expectation values are taken from the TAMM model, while costs will be obtained from regional studies (e.g., Rahm 1981 and Dutrow et al. 1982). This timber resources inventory projection model would make projections by ten-year intervals, while linked to the annual TAMM market model.

OTHER MODELING CONSIDERATIONS

Applications of techniques for analyzing timber investment strategies are numerous, and many variations have been applied to the broad range of timber species across the nation. A cross section of these timber investment analysis techniques are listed by region in appendix C, which also includes sources of cost information useful for investment analyses. These techniques have frequently been constructed to analyze stand level treatment possibilities, and they are typically designed for analyses at substate levels (e.g., Hepp 1982). Thus, analysis of the biological and economic characteristics of alternative timber management schemes at aggregate levels would probably require considerable adjustments in associated timber growth and yield modeling to better address the less detailed but more extensive data needs of aggregate analyses.

All of the major timber investment analysis techniques currently available are based on normative decision rules, which assume that owner objectives are generally based on maximization of economic gain from the timber resource alone. No positive aggregate timber investment model has been reported, and timber supply analysts face the question of how to represent adequately realistic future price expectations mechanisms and likely supply responses by stumpage producers. Because planned supply responses or investment decisions involve estimates of the future based on imperfect knowledge regarding stumpage prices, technology, yields, institutions, etc., those future estimates are subject to error. Those errors give rise to differences between planned and realized supply response (Jensen and Day 1961, Stone 1970), and little is known regarding the extent of this gap for timber investments. Most timber investment analyses utilized in examining future timber supply levels also usually assume that all timber investments actually implemented will be carried to maturity at a certain productive level.

This latter assumption may be too optimistic in some cases because of evidence of investment failures and land use changes cited in several studies.[4] Studies of the retention and condition of timber investments initiated through public programs are listed in appendix D. In general, an inconsistent and rather meager information base exists to support the appropriate degrees of adjustment of physical and financial yields of timber investments to account for unforeseen productivity reductions and land use changes. This is particularly true for nonindustrial, private timber investments, which often are managed by several different landowners over a maturation period that typically spans at least several decades.

The various approaches to modeling aggregate timber investment have generally been normative in nature. They have emphasized different biological and economic dimensions, especially as they relate to the dynamics of timber supply. Static optimization techniques have been utilized to investigate displacement from equilibrium positions based on competitive market conditions, specified constraints, and the objective of profit maximization, but the explicit time path of variable changes is not predicted. A hybrid framework that uses short-run, empirically derived harvest relations in conjunction with normative long-term timber investment modeling in a dynamic analysis supports the first-generation TAMM model.

The proliferation in the application of operations research techniques in forestry over the past several decades has also led to a large body of literature on timber investment analyses using mathematical programming models suited to electronic data processing (e.g., Brodie et al. 1978). The mathematical basis of optimization techniques necessarily implies abstract representations of biological and social systems, with approximations and simplifying assumptions generally required if the model is to be tractable. The proper criterion for judging whether the fomulated model is then a valid representation is whether it predicts the relative effects of alternative courses of action with sufficient accuracy to permit a sound decision (Hillier and Lieberman 1980). Such determination is quite subjective with respect to timber investment because long maturation periods hinder timely objective validation (and consequent modification, if needed).

AGGREGATION AND UNCERTAINTY CONSIDERATIONS

Estimating the validity of aggregate models and the concurrent degree of uncertainty associated with aggregate timber supply studies is a major problem. The degree of uncertainty inherent in estimating future components of timber supply is strongly related to the aggregation schemes employed, which by their nature condense diverse and complex relationships into a relatively small number of essential characteristics. The broad geographical range of most aggregate analyses invariably includes diverse owner classes with differing

timber management motivations, institutional constraints, resource and market knowledge, etc. Not only does this imply that predicting future timber supply is difficult, but in many situations substantial uncertainty exists with regard to current areas, volumes, ecological capabilities, prices, etc. (Bentley 1981).

Aggregation and uncertainty in timber supply modeling are related in part to the quantity and quality of historical data available as a basis for projection. Data deficiencies vary with respect to biological and economic dimensions of timber supply modeling, and also within these two broad categories. The levels of timber growth and yield data have been augmented significantly during the last several decades; substantial problems remain, however, regarding the suitability of such data for purposes of modeling responses to an array of management treatments.

Availability and quality of data for economic characteristics of timber management is also highly variable; data are particularly deficient in certain areas. A comprehensive data base for modeling landowner response to alternative market conditions does not exist; therefore, consideration of the dynamic nature of human interactions with biological and economic systems in the real world is quite limited. These deficiencies have forced analysts to employ less data-demanding models, often limiting the expansion of analyses to adequately include other resource interactions and impeding the construction of timber supply analyses at less aggregated levels. Strategies for dealing with data limitations are offered by Rose et al. (1981), while Hamilton (1978) and Lewis and Ellefson (1983) discuss related aspects of required levels of precision with respect to information needs for forest management.

Even with ideal data sources, however, determination of the mode of data aggregation for regional and national timber supply studies would likely not involve a straightforward decision process. Appropriate geographic bases sometimes vary greatly for analyzing ecological, social, and economic concerns in supply studies that include multiresource and institutional considerations. Although aggregation patterns may have a substantial bearing on the quality of supply analysis results, a set of useful aggregation guidelines based on adequate quantitative considerations has not emerged. At least initially, aggregation schemes are dictated by the objectives of a given study, but the direction of later adjustments in response to data availability is often not predictable.

Teeguarden (1977), in discussing the complex of factors involved in aggregation considerations for RPA Assessments, suggests that relatively homogeneous ecosystems be the lowest level of analysis, with subsequent aggregation to regions and to the nation. Marty (1969) and Beuter (1979) have suggested the need for less aggregated geographic and ownership groupings than have been utilized in national timber appraisals. While other suggestions can be found in the literature, no complete set of readily transferable guidelines based on quantitative or economic principles is available to aid in devising aggregation schemes for timber supply studies. The question of appropriate level of aggregation also needs to be examined regarding timber demand as well.

Two additional aspects of data aggregation that may cause problems in timber supply modeling pertain to nonlinear systems and variance of aggregates.[9] In the first instance, aggregation can cause bias in systems that are nonlinear, particularly for systems with many step functions (e.g., decisions to harvest, depending on volume or costs). The second case pertains to whether a particular model adequately represents the effects of variance in aggregates. For systems with strong positive feedback, ignoring variance may introduce bias (e.g., ignoring the variability of growth rates from the mean for large, dominant trees may produce underestimation of growth).

Aggregate timber supply results are generally based on analytical techniques dependent upon a mixture of experimental and nonexperimental data sources, with little (if any) indication of the overall statistical reliability of the ultimate results. The manner in which such statistical problems might interact or even be compounded over relatively long timber supply projection periods has generally not been addressed. While the problem of combining techniques or data of varying statistical reliability is not unique to timber supply analyses, the particular mixture of specific data problems and long time periods involved in timber supply studies create some special statistical concerns. Propagation of error does appear to limit the usefulness of large, relatively complex models.

One general approach used to address these problems has been the use of sensitivity analyses, the testing of the influence of changes in input items or assumptions on model results. Sensitivity analyses are especially relevant for mathematical programming techniques that are widely used in forest land planning, given the long planning horizons and the assumption of certainty for model imputs.

Sensitivity analyses have been applied in various fashions for timber supply analyses. For example, Frayer and Jones (1970) use a Monte Carlo technique to investigate the effects of each input item on timber stand projection variability. Results indicate that sampling errors for growth, mortality, removal, and ingrowth parameters largely determine projection variability. Goforth and Mills (1975) devised a technique to determine degree of data error required to influence the outcome of timber investment analyses.

One proposal for improving credibility of natural resource supply forecasts involves the comparison of a series of relatively short-term projections with one continuous projection.[5] In this approach, reexamination (and readjustment if necessary) of assumptions and techniques are possible at each breakpoint. Another suggestion involves definition of a systematic procedure to ensure that each component of the projection process and the overall process itself is examined for validity by specialists other than the forecaster/analyst and the potential users.[5]

Reducing the degree of uncertainty in timber supply analyses, or at least not unduly obscuring it in describ-

ing results of such studies, is a primary consideration in devising aggregation schemes. Much has been written on the general topic of uncertainty associated with investment analyses and planning (e.g., Borch 1968, Arrow and Lind 1970), with applications to forest land use planning discussed by Dowdle (1962), Marty (1964), Thompson (1968), Teeguarden (1969), Lundgren and Thompson (1972), and Fight and Bell (1977), among others. As noted in the previous section, Hoganson (1981) offers a specific approach for addressing the problem of uncertainty and accountability in stand-level optimization (i.e., linear programming) modeling by reformulating the linear programming problem within a simulation framework. However, there appear to be no standard pathways to follow in evaluating and tempering aggregate forest investment analysis or supply projections with regard to uncertainty. Zones of uncertainty, usually expanding greatly with time, are sometimes assigned to forecasted estimates in timber supply studies. However, their estimation and use appear to be rather subjective in nature.

A relatively large degree of uncertainty in timber supply analyses is related to the estimation of future technological changes. This refers to both innovation and implementation of technologies across diverse owner settings. According to economic theory, production function frontiers are based on application of the most efficient technology, which therefore implies a fixed technology base over the production period; however, production processes that stretch over several decades at a minimum suggest that this assumption may not be valid. While many recognize that substitution of other inputs (e.g., genetically improved trees) for land in timber production will increase in the future, precise forecasts of the rate and actual composition of the technical change are difficult to obtain. Heady (1952) has outlined some basic principles to consider in attempting to approximate the direction of the impact of technical change; these are based on the nature of the technical change and demand-supply characteristics of products (Castle 1977).

Aggregate timber supply studies can provide critical clues to issues regarding natural resources availability, but often such studies are questioned because adequate measures of risk or uncertainty are not provided. Most aggregate studies have employed deterministic models that provide only a point estimate of the outcome for a specified set of assumptions and timber management strategies. This is again related in part to data problems. It is not uncommon for timber growth and yield projections to be published without any meaningful indication of changes in the level of reliability over the projection period.

In summary, given that substantial uncertainty and aggregation bias might be associated with aggregate timber supply studies, the degree of sophistication warranted in a study's framework and underlying modeling techniques is largely a judgmental matter. Standard statistical tests or other objective guidelines are very difficult to apply in a comprehensive manner, largely because of the quality and mixture of available data. A key question in the planning stages of a timber supply study is whether the study approach is consistent and efficient in terms of the stated objective.[6] However, currently there are difficulties in determining changes in the quality of projection results needed to improve decisionmaking to selected degrees. This has also impeded rigorous and objective evaluations of model adequacy.

OVERVIEW OF METHODOLOGY

Techniques and supporting data bases for analyzing aggregate timber supplies have evolved at different rates for the four major analytical components reviewed: forest land use allocation, growth and yield of the timber resource, removals or harvest, and timber investments over time. Aggregate timber supply analyses prior to 1970 typically depicted timber supplies in physical or biological dimensions, with relatively little analysis of their relationship to market forces. Applied analytical techniques have generally evolved, however, from relatively simple ratio and trend analyses to the use of complex econometric techniques in modeling the equilibrium of supply and demand.

The allocation of land to timber production has been exogenously determined in national timber assessments, with adjustments in a residual timberland base reflecting changes in higher valued land uses. Systematic methodologies for projecting timberland acreages have been based largely on economic optimization criteria (e.g., Hyde 1980), with notable exceptions being Markov land use simulation (e.g., Burnham 1973) and econometric approaches (e.g., White and Fleming 1980).

The accuracy of results from projecting timberland acreages with techniques that embody optimization criteria has not been satisfactory in some cases, especially with regard to nonindustrial, private lands. Simulation techniques applied in attempting to remedy this situation have also met with limited success, primarily because of land use data limitations. Documented information for historical timberland acreages is characterized by irregular time frames and nonstandard classification criteria among major data sources.

Assuming that a method for characterizing the forest resource has been selected and the resource has been stratified on the basis of such a characterization, timber inventory projection models are used to project representative units of each stratum (or the entire stratum) over time in timber supply analyses. For example, simultaneous growth and yield equations (e.g., Sullivan and Clutter 1972) can be utilized for stand-level projections for a given initial density, age, site, etc., stratum. In an alternative approach, the STEMS model (USDA Forest Service 1979) generates projections on an individual-tree basis for a particular stratum.

Given the diversity of species types and physical settings, timber inventory modeling has evolved according to two approaches: direct and indirect methods. Direct methods involve modeling growth and yield for forest areas using only sampling information for those areas

(i.e., applying sample data directly back to the population from which the sample was obtained). An example is a stand table projection technique such as the TRAS model, which applies rates of change (e.g., mortality rate) to a set of initial stand conditions (Alig et al. 1982). TRAS has been used in several regional and national timber supply appraisals, but its design makes it somewhat inflexible for modeling impacts of alternative timber management strategies.

Indirect timber inventory projection methods are applied to subject stands larger than those from which the original growth and yield data are obtained, and essentially involve a two-phase process. Whole stand yield tables (McArdle et al. 1961) and variable density growth and yield tables or models (Buckman 1962) comprise the two broad classes of indirect methods. Variable density growth and yield models may be used to generate yield tables, and there are three major classes of these variable density models: whole stand (Buckman 1962), size class and/or growth component (Moser 1974), and individual-tree simulation models (Stage 1973). The first two classes rely upon aggregate stand characteristics such as number of trees or basal area in modeling forest development. The more recently developed individual-tree simulation models describe stands on the basis of characteristics of individual trees.

Individual-tree models are classified according to whether or not they incorporate intertree distance within the projection framework. Intertree distance-independent models are represented by the STEMS model (USDA Forest Service 1979) and the Prognosis model (Stage 1973). These models do not consider spatial patterns or individual-tree locations. Consequently, they are operationally faster than distance-dependent models (e.g., Daniels and Burkhart 1975), presumably without a significant trade-off in terms of modeling precision for aggregate timber supply studies. Distance-dependent models can provide relatively detailed evaluations of timber management alternatives, but are relatively taxing in terms of data requirements and computer time.

The design and implementation of an inventory projection system that would improve upon current capabilities for aggregate timber supply analyses are buffeted by multifaceted considerations. Data availability, accuracy requirements, cost effectiveness, time and personnel constraints, and manageability are examples of interrelated (and often conflicting) considerations that are difficult to weigh because of quantification problems. While the growing sophistication of computer programming technology facilitates construction of individual models with larger storage and computation capabilities, the reliance upon a single model (e.g., TRAS) in future aggregate timber supply modeling may diminish as the state of the art evolves. It is unlikely that a single growth model could provide the most efficient growth estimates for all species and conditions. Also, the incorporation or adaptation of all of the component relationships needed to apply any one model to all species and conditions would likely be impeded by translation and data availability problems. Linkage of models, or the aggregation of results from distinct models (using statistical reliability standards), appears to offer substantial promise, though coordination problems will likely be substantial.

Timber inventory projection models suitable for large-scale analyses have generally been developed separately from economic analysis techniques, the latter having been subsequently linked to them for the purpose of modeling the interrelationships between biological development of timberland and human intervention. This has somewhat hindered supply analysts from examining impacts arising from shifts in timber management intensity suggested by investment analyses.

Harvest flow models interface with timber inventory projection models in modeling the impacts on inventory development that result from adjusting timber inventory levels in response to harvest decisions. Harvest flows are often calculated as part of an overall, optimal, timber management package based upon long-run considerations (e.g., Hyde 1980). However, in the 1980 RPA Assessment, such harvest flows were modeled as short-run functions of stumpage price and timber inventory levels (Adams and Haynes 1980).

Simulation and optimization techniques have been utilized separately or in various mixtures in modeling aggregate harvest flows. These approaches differ with respect to the assumed basis of stumpage supply responses of producers, including the posited intertemporal linkage between harvests and long-range investments. The TAMM model (Adams and Haynes 1980) simulates future harvest flows by using econometrically estimated short-run equations based on observed values from a historical period approximately several decades in length. An optimization model such as FORPLAN (Johnson et al. 1980) seeks to maximize (or minimize) the value of an objective function that includes values for decision variables representing management practices for specific areas. Thus, simulation models have been employed to project timber supply trends based on historical patterns or other assumptions, while optimization models can estimate potential supply responses linked to efficient shifts in timber management on some lands (assuming certain goals). The basic distinction is between simulating how the system tends to operate, in contrast to how it could operate according to some norm or optimality rule.

Simulations of timber supply activities in aggregate timber supply studies have typically been made with econometric techniques, which use statistical methods to quantify economic relationships. Econometric models for aggregate timber supply processes often include several variables that are exogenous to the model, thus leading to a partially open modeling structure. In particular, macroeconomic variables (e.g., interest rates) may exert large influences on timber supply activities. These are quite difficult to forecast for future conditions, particularly when the long time horizons characteristic of forestry planning are considered. Other simulation techniques that might be used in place of or in conjunction with econometric techniques are stochastic simulation and system dynamics. In particular,

system dynamics may allow a more explicit method for modeling the complex interactions that characterize timber supply processes, while providing a general level of understanding regarding the associated dynamic tendencies over the long time periods (Meadows 1980).

While simulation models are readily adaptable to the modeling of aggregate harvest flows, optimization techniques such as linear programming encounter difficulties regarding specification of appropriate objective functions and constraint equations for regional or national analyses (McCarl and Spreen 1980). This problem is significant for both private and public ownerships. The extent of deviation of actual harvesting patterns from "optimal" timber harvest and management strategies assumed or portrayed in optimization analyses is presently unknown, but some evidence exists concerning management activities applied to cost-shared timber investments on nonindustrial private lands (e.g., Kurtz et al. 1980).

Modeling of aggregate timber investment behavior has been integrated with that for harvest flows in several different ways. An example of incorporating timber investment patterns based on optimization criteria within an overall timber supply simulation approach is the TAMM modeling applied for the 1980 RPA Assessment (Adams et al. 1982). A different approach is exemplified by the long-term timber supply potential model developed by Lyon and Sedjo (1983). This is based on optimal control theory and projects harvest and investment levels during both transitional and steady-state phases. Such an approach allows simultaneous determination of harvest and investment levels over an analysis period; it has not been extensively applied and tested to date.

The current array of timber investment analysis techniques at the stand level varies considerably across the country, primarily because the degree of sophistication of the underlying growth and yield modeling is not uniform across regions. Timber growth and yield characteristics differ so greatly across some geographical locations in terms of species, physiography, climate, and other factors, that separate growth and yield models must be linked to relatively standardized economic analysis tools for particular regions. As a consequence, differences in the evolution of data collection and biological response modeling efforts for various packages of timber management treatments have resulted in varying capabilities for evaluating timber investment opportunities in different parts of the country.

Specific areas of improvement needed in long-term timber management modeling include positive timber investment modeling and more in-depth examination of the dynamics of timber inventory development in response to varying degrees and timing of investments. At present, no positive models of aggregate timber investment behavior exist. Empirical work devoted to the statistical testing of timber investment theories has been quite limited, and no fully satisfactory or widely accepted theory of aggregate, long-term timber investment has been established. A better understanding of private timber investment decisionmaking is required, particularly with respect to the processes of economic expectation formation (e.g., as for stumpage prices) for conditions that may not actually materialize for several decades at a minimum. Appropriate levels of detail and abstraction for aggregate timber investment models also require careful scrutiny, including the establishment of useful measures of general aggregate investment behavior.

Investment modeling based on the assumption of timber profit maximization by owners may represent an upper limit or overestimation of actual investment, in light of the currently deficient data and analyses related to other objectives for various owner groups. From an overall perspective, generalizations regarding appropriate levels of abstraction and aggregation in aggregate timber supply studies are tenuous; this is due in part to the varying objectives of such studies and to difficulties in verifying whether harvest and investment patterns depicted by these models adequately reflect actual occurrences.

The degree and timing of future improvements in aggregate timber supply analysis may depend upon measures taken to strengthen existing data sources. Data deficiencies have been alluded to within numerous timber supply studies, which themselves have generally drawn on a variety of data sources. With respect to basic timber supply data, timber resource data is sometimes criticized as being inadequate for modeling purposes; however, economic data may be even less adequate. This has particularly hampered econometric analyses, which require reasonably long series of consistent price and production data. For example, data on timber production and transportation costs based on location and accessibility considerations have not been assembled or organized in readily retrievable forms for use in extending supply modeling capabilities.

The quality dimensions of timber supply represent another instance in which data deficiencies have impeded modeling. Timber supply at aggregate levels is comprised of many species, sizes, and grades of trees or logs, each of which may have a distinct price. Existing data do not presently allow these differences to be extracted or monitored.

Some of the primary improvements needed in aggregate timber supply data include:

1. Levels of private timber harvest by region and owner group.
2. Timber inventory by region and owner group.
3. Socioeconomic characteristics of forest owners (e.g., income)
4. Actual timber investment behavior by forest owners.
5. Forest land management opportunities by region and owner group (collected on a periodic basis).[8]

The bulk of the empirical aggregate timber supply analyses can be described without reference to anything but the most basic microeconomic theory. While the transition from theoretical abstraction to empirical reality has been hindered by data problems, numerous opportunities exist to build upon basic timber supply

theory a structure that is more flexible and realistic with regard to the diverse ownership settings.

Ultimately, research may provide an overall model capable of representing aggregate timber supply according to the theory of the rational forest owner.[8] This will entail the simultaneous determination of the levels of timber harvest, intensity of timber management, and land area devoted to the timber growing enterprise over time (along with supporting timber inventory projection capabilities). It will require more attention to the systems structure of the analytical problem (e.g., feedback loops and performance criteria) which in turn may provide a framework for integrating the components of aggregate timber supply analysis. An additional requirement is a better understanding of owner objectives, including the nature and extent of interest in market and nonmarket forest products and the "role" of the forest enterprise in the overall operations of a forest owner, as well as the role of forestry in local, regional, and national economies. However, given the state of the art and data deficiencies, analysts will be forced in the interim to separate the overall problem into smaller, more tractable components, as outlined in this report.

LITERATURE CITED

Ackley, Gardner. 1978. Macroeconomics: Theory and policy. 738 p. Macmillan Publishing Co., Inc., New York, N.Y.

Adams, Darius M. 1974. Forest products prices and National Forest timber supply in the Douglas-fir region. Forest Science 20:243-259.

Adams, Darius M. 1975. The response of softwood stumpage and end product prices to changes in National Forest timber harvest schedules. [Report of a Cooperative Aid Research Agreement with the Pacific Northwest Forest and Range Experiment Station]. 6 p. plus appendixes. USDA Forest Service Portland, Oreg.

Adams, Darius M. 1977. Effects of National Forest timber harvest of softwood stumpage, lumber, and plywood markets: An econometric analysis. Oregon State University Forest Research Lab Research Bulletin 15, 50 p. Corvallis.

Adams, Darius M., and A. R. Ek. 1974. Optimizing the management of uneven-aged forest stands. Canadian Journal of Forest Resources 4:274-287.

Adams, Darius M., and A. R. Ek. 1975. Derivation of optimal management guides for individual stands. p. 132-147. In Systems analysis and forest resource management. J. C. Meadows, B. B. Bare, K. W. Ware, and C. Row, editors. Society of American Foresters, Bethesada, Md.

Adams, Darius M., and Richard W. Haynes. 1980. Softwood timber assessment market model: Structure, projections, and policy simulations. Forest Science Monograph No. 22, 64 p.

Adams, Darius M., N. L. Dennis, and J. B. Schmerhel. 1974. Program SHAF for simulating the harvest of uneven-aged stands of northern hardwoods. University of Wisconsin, Department of Forestry, Staff Paper Series No. 1. 8 p., plus appendix. Madison.

Adams, Darius M., Richard W. Haynes, George F. Dutrow, Richard L. Barber, and Joseph M. Vasievich. 1982. Private investment in forest management and the long-term supply timber. American Journal of Agricultural Economics 64(2):232-241.

Adams, Darius M., Richard W. Haynes, Thomas J. Mills, David Shearer, and Steven Childress. 1979. Production, consumption, and prices of softwood products in North America-regional time series data, 1950-1976. Research Bulletin 27, 43 p. Oregon State University, Forest Research Laboratory, Corvallis.

Adams, F. Gerard, and John Blackwell. 1973. An econometric model of the United States forest products industry. Forest Science 19:82-96.

Alexander, R. R., Wayne D. Shepperd, and C. B. Edminster. 1975. Yield tables for managed even-aged stands of spruce-fir in the Central Rocky Mountains. USDA Forest Service Research Paper RM-134, 20 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Alig, Ralph J., Glen E. Brink, Marcus H. Goforth, Vernon J. LaBau, and Thomas J. Mills. 1982. Users's manual for TRAS-1980: An expanded version of the TRAS projection system. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, 63 p. Fort Collins, Colo. [Unnumbered publication].

Alig, Ralph J., Thomas J. Mills, and Robert L. Shackelford. 1980. Most Soil Bank plantings in the South have been retained; some need follow-up treatments. Southern Journal of Applied Forestry 4:60-64.

Alimi, R. J., and J. P. Barrett. 1977. Computer and tabular growth simulation of mixed conifer-hardwood stands in the Northeast. New Hampshire Agricultural Experiment Station Research Report 61, 56 p. Durham.

Amidon, E. L., and G. S. Akin. 1968. Dynamic programming to determine optimum levels of growing stock. Forest Science 14:287-291.

Anderson, Walter C. 1968. Rating investments for improving Georgia timber stands. Land Economics 44(1):121-127.

Anderson, Walter C., and Sam Guttenberg. 1971. Investor's guide to converting southern oak-pine types. USDA Forest Service Research Paper SO-72, 10 p. Southern Forest Experiment Station, New Orleans, La.

Apple, R. L. 1982. An analysis of FORPLAN. M. S. thesis, 72 p. University of Minnesota, College of Forestry, St. Paul.

Arney, James D. 1974. An individual tree model for stand simulation in Douglas-fir. p. 38-46. *In* Growth models for tree and stand simulation. J. Fries, editor. Research Note 30, Royal College of Forestry, Department of Forestry Yield Research, Stockholm, Sweden.

Arrow, Kenneth J. 1976. The rate of discount for long-term public investment. In Energy and the environment. H. Ashley, R. Rudman, and C. Whipple, editors. Pergamon Press, Inc., New York, N.Y.

Arrow, Kenneth J., and R. C. Lind. 1970. Uncertainty and the evaluation of public investment decisions. American Economic Review 60:364-378.

Ashton, P. G., J. B. Pickens, C. Ohlander, and B. Benninghoff. 1980. Many resources, many uses: A system analysis approach to renewable resource development. Water Resources Bulletin 16(4):738-744.

Avery, T. E., and H. E. Burkhart. 1983. Forest measurements. Third edition. 331 p. McGraw Hill, New York, N.Y.

Barber, Richard L. 1980. A methodology for evaluation of RPA timber production enhancement programs using the RPA assessment model. Master of Forestry paper, 43 p. Oregon State University, Department of Forest Management, Corvallis.

Bare, B. Bruce. 1971. Applications of operations research in forest management: A survey. Quantitative Science Paper No. 26, 57 p. Center for Quantitative Science, University of Washington, Seattle.

Barnes, R. L. 1955. Growth and yield of slash pine plantations in Florida. Report 3, 23 p. University of Florida, School of Forestry Research. Gainesville.

Beck, D. E., and Lino Della-Bianca. 1970. Yield of unthinned yellow-poplar. USDA Forest Service Research Paper SE-58, 20 p. Southeastern Forest Experiment Station, Asheville, N.C.

Beck, D. E., and Lino Della-Bianca. 1972. Growth and yield of thinned yellow-poplar. USDA Forest Service Research Paper SE-101, 20 p. Southeastern Forest Experiment Station, Asheville, N.C.

Bell, Enoch F. 1976. Goal programming for land use planning. USDA Forest Service General Technical Report PNW-53, 12 p. Pacific Northwest Forest and Range Experiment Station, Portland, Oreg.

Bell, Enoch F. 1977. Mathematical programming in forestry. Journal of Forestry 75:317-319.

Bennett, F. A. 1970a. Yields and stand structural patterns for old-field plantations of slash pine. USDA Forest Service Research Note SE-60, 81 p. Southeastern Forest Experiment Station, Asheville, N.C.

Bennett, F. A. 1970b. Variable density yield tables for managed stands of natural slash pine. USDA Forest Service Research Note SE-141, 7 p. Southeastern Forest Experiment Station, Asheville, N.C.

Bennett, F. A., and J. L. Clutter. 1968. Multiple-products yield estimates for unthinned slash pine plantations—pulpwood, sawtimber, gum. USDA Forest Service Research Paper SE-35, 21 p. Southeastern Forest Experiment Station, Asheville, N.C.

Bennett, F. A., C. E. McGee, and J. L. Clutter. 1959. Yield of old-field slash pine plantations. USDA Forest Service Station Paper 107, 19 p. Southeastern Forest Experiment Station, Asheville, N.C.

Bentley, William R. 1981. Research needed to support industrial forestry planning. p. 210-213. In Proceedings of the International Union of Forestry Research Organizations (IUFRO), Symposium on forest management planning: Present practice and future decisions. [Blacksburg, Va., August 18-20, 1980] Publication FWS-1-81, 228 p. Virginia Polytechnic Institute and State University, School of Forestry and Wildlife Resources, Blacksburg.

Bentley, William R., and Lawrence S. Davis. 1976. Assessment of long-term forecasting in timber economics. 53 p. [Background report for the Timber Harvest Scheduling Issues Study] USDA Pacific Northwest Forest and Range Experiment Station, Portland, Oreg.

Berck, Peter. 1979. The economics of timber: A renewable resource in the long-run. Bell Journal of Economics 10:447-462.

Beuter, John H. 1979. Some problems with the 1980 RPA timber assessment. In Proceedings, Timber supply: Issues and options, p. 44-46. [San Francisco, Calif., October 2-4, 1979] Forest Research Society, 218 p. Madison, Wis.

Beuter, John H., and Jeffrey K. Handy. 1974. Economic guidelines to reforestation for different ownerships: A case study for the Coast Range of western Oregon. Research Paper 23, 69 p. Oregon State University, School of Forestry, Corvallis.

Beuter, John H., K. N. Johnson, and H. L. Schuerman. 1976. Timber for Oregon's tomorrow—An analysis of reasonably possible occurrences. Research Bulletin 19, 50 p. Oregon State University, Forest Research Laboratory, Corvallis.

Binkley, Clark S. 1979. Timber supply from private nonindustrial forests, and economic analysis of landowner behavior. Ph.D. thesis, 127 p. Yale University, New Haven, Conn.

Binkley, Clark S. 1981. Timber supply from private nonindustrial forests: A microeconomic analysis of landowner behavior. School of Forestry and Environmental Studies Bulletin No. 92, 97 p. Yale University, New Haven, Conn.

Borch, K. H. 1968. The economics of uncertainty. 227 p. Princeton University Press, Princeton, N.J.

Botkin, D. B., J. F. Janak, and J. R. Wallis. 1972. Some ecological consequences of a computer model of forest growth. Journal of Ecology 60:849-872.

Boyce, Stephen G. 1977. Management of eastern hardwood forests for multiple benefits (DYNAST-MB). USDA Forest Service Research Paper SE-168, 116 p. Southeastern Forest Experiment Station, Asheville, N.C.

Boyce, Stephen G. 1978. Management of forests for timber and related benefits (DYNAST-TM). USDA Forest Service Research Paper SE-184, 140 p. Southeastern Forest Experiment Station, Asheville, N.C.

Bradley, Dennis P. 1972. Improving forest inventory with access data measures of transport distance and cost to market. USDA Forest Service Research Paper NC-82, 21 p. North Central Forest Experiment Station, St. Paul, Minn.

Broderick, Stephen H., John F. Thurmes, and W. David Klemperer. 1982. Economic evaluation of old-field loblolly pine plantation management alternatives. Southern Journal of Applied Forestry 6(1):9-15.

Brodie, J. Douglas, and Dietmar W. Rose. 1975. Simulation of jack-pine management with alternate control strategies for the jack-pine budworm. Research Bulletin R2734, 32 p. University of Wisconsin, Madison.

Brodie, J. Douglas, Darius M. Adams, and Chiang Kao. 1978. Analysis of economic impacts on thinning and rotation for Douglas-fir, using dynamic programming. Forest Science 24(4):513-522.

Brodie, J. Douglas, and Chiang Kao. 1979. Optimizing thinning in Douglas-fir with three-descriptor dynamic programming to account for accelerated diameter growth. Forest Science 25(4):665-672.

Brodie, J. Douglas, and Dietmar W. Rose. 1975. Simulation of jack-pine management with alternate control strategies for the jack-pine budworm. Research Bulletin R2734, 32 p. University of Wisconsin, Madison.

Brooks, David J. 1983a. SPATS: An age-class inventory projector for the South. Oregon State University, Department of Forest Management, Corvallis. (In press).

Brooks, David J. 1983b. Southern timber supplies to the year 2000: Alternative projections. Oregon State University, Department of Forest Management, Corvallis. (In press).

Bruce, D., D. J. DeMars, and D. L. Reukema. 1977. Douglas-fir managed yield simulator—DFIT user's guide. USDA Forest Service General Technical Report PNW-57, 26 p. Pacific Northwest Forest and Range Experiment Station, Portland, Oreg.

Buckman, R. E. 1962. Growth and yield of red pine in Minnesota. USDA Technical Bulletin 1272, 50 p. Lakes States Forest Experiment Station, St. Paul, Minn.

Buchman, Roland G., and Stephen R. Shifley. 1983. Guide to evaluating forest growth projection systems. Journal of Forestry 81(4): 232-243.

Buongiorno, Joseph, and Bruce R. Michie. 1980. A matrix model of uneven-aged forest management. Forest Science 26(4):609-625.

Burkhart, Harold E., Quang V. Cao, and Kenneth D. Ware. 1981. A comparison of growth and yield prediction models for loblolly pine. Publication FWS-2-81, 59 p. Virginia Polytechnic Institute and State University, School of Forestry and Wildlife Resources, Blacksburg.

Burkhart, Harold E., R. C. Parker, and R. G. Oderwald. 1972a. Yields for natural stands of loblolly pine. Publication FSW-2-72, 63 p. Virginia Polytechnic Institute and State University, School of Forestry and Wildlife Resources, Blacksburg.

Burkhart, Harold E., R. C. Parker, M. R. Strub, and R. G. Oderwald. 1972b. Yields of old-field loblolly pine plantations. Publication FWS-3-72, 51 p. Virginia Polytechnic Institute and State University, School of Forestry and Wildlife Resources, Blacksburg.

Burkhart, Harold E., and M. R. Strub. 1974. A model for simulation of planted loblolly pine stands. p. 128-135. *In* Growth models for tree and stand simulation. J. Fries, editor. Research Note 30, Department of Forestry Yield Research, Stockholm, Sweden.

Burnham, Bruce O. 1973. Markov intertemporal land-use simulation model. Southern Journal of Agricultural Economics 5(1):235-258.

Callahan, John C., and Robert P. Smith. 1974. An economic analysis of black walnut plantation enterprises. Resource Bulletin 912, 20 p. Purdue University, West Lafayette, Ind.

Candler, W., J. Fortuny-Amat, and B. McCarl. 1981. The potential role of multilevel programming in agricultural economics. American Journal of Agricultural Economics 63(3):521-531.

Cao, Quang V., Harold E. Burkhart, and R. C. Lemin, Jr. 1982. Diameter distributions and yields of thinned loblolly pine plantations. Publication FSW-1-82, 62 p. Virginia Polytechnic Institute and State University, School of Forestry and Wildlife Resources, Blacksburg.

Castle, Emery N. 1977. Research needs in forest economics and policy: An interpretative and evaluative summary. p. 3-36. *In* Research in forest economics and forest policy. Marion F. Clawson, editor. Research Paper R-3, 555 p. Resources for the Future, Washington, D.C.

Chambers, C. J., and F. M. Wilson. 1972. Empirical yield tables for the Douglas-fir zone. DNR Report 20R. 16 p. Washington State Department of Natural Resources, Olympia.

Chambers, C. J., and F. M. Wilson. 1978. Empirical yield tables for the true western hemlock zone. DNR Report 22R. 14 p. Washington State Department of Natural Resources, Olympia.

Chappelle, Daniel E., and Robert W. Sassaman. 1968. A computer program for scheduling allowable cut using either area or volume regulation during sequential planning periods. USDA Forest Service Research Note PNW-93, 9 p. Pacific Northwest Forest and Range Experiment Station, Portland, Oreg.

Chappelle, Daniel E., M. Mang, and R. C. Miley. 1976. Evaluation of Timber RAM as a forest management planning model. Journal of Forestry 74:288-293.

Chappelle, Daniel E., and Thomas C. Nelson. 1964. Estimation of optimal stocking levels and rotation ages of loblolly pine. Forest Science 10:421-502.

Clark, Colin W. 1976. Mathematical bioeconomics: The optimal management of renewable resources. 352 p., John Wiley and Sons, New York, N.Y.

Clark, Peter K. 1979. Investment in the 1970's: Theory, performance, and prediction. Brookings Papers on Economic Activity 1(1979):73-113.

Clawson, Marion F. 1979. The economics of U.S. non-industrial private forests. Research Paper R-4. Resources for the Future, John Hopkins University Press, Baltimore, Md.

Clawson, Marion F., and William Hyde. 1976. Managing the forests of the Coastal Pacific Northwest for maximum social return. p. 179-206. In Timber policy issues in British Columbia. University of British Columbia Press, Vancouver, Canada.

Clawson, Marion F., and C. L. Stewart. 1965. Land use information: A critical survey of U. S. statistics including possibilities for greater uniformity. 402 p. Resources for the Future, John Hopkins University Press, Baltimore, Md.

Clutter, J. L. 1963. Compatible growth and yield models for loblolly pine. Forest Science 9(3):355-371.

Clutter, J. L., and B. J. Allison. 1974. A growth and yield model for *Pinus radiata* in New Zealand. p. 136-160. In Growth models for tree and stand simulation. p. 136-160. J. Fries, editor. Research Note 30, Royal College of Forestry, Department of Forestry Yield Research. Stockholm, Sweden.

Cohan, David. 1982. Forest management and timber industry market equilibrium. Ph.D. dissertation, 246 p. Stanford University, Palo Alto, Calif.

Coile, T. S., and F. X. Schumacher. 1964. Soil-site relations, stand structure, and yields of slash and loblolly pine plantations in the southern United States. 296 p. T. S. Coile, Inc. Durham, N.C.

Conkin, Merle E. 1971. Cost of timber management for selected areas in the northern region of the United States. M.S. thesis, 103 p. Iowa State University, Ames.

Cox, Greg. 1980. Estimation of silvicultural treatment costs and identification of major cost determinants. M.S. thesis, 147 p. Colorado State University, Fort Collins.

Crookston, N. L. 1978. Predicting the outcome of management activities in mountain pine beetle susceptible lodgepole pine stands. Proceedings of the Society of American Foresters 1978:276-280.

Curtis, Robert O. 1967. A method of estimation of gross yield of Douglas-fir. Forest Science Monograph 13. 24 p.

Curtis, Robert O. 1972. Yield tables past and present. Journal of Forestry 70:28-32.

Curtis, Robert O., Gary W. Clendenen, and Donald J. DeMars. 1981. A new stand simulator for coast Douglas-fir: DFSIM user's guide. USDA Forest Service General Technical Report PNW-128, 79 p. Pacific Northwest Forest and Range Experiment Station, Portland, Oreg.

Dahms, W. G. 1964. Gross and net yield tables for lodgepole pine. USDA Forest Service Research Paper PNW-8. 14 p. Pacific Northwest Forest and Range Experiment Station, Portland, Oreg.

Dahms, W. G. 1975. Gross yield of central Oregon lodgepole pine. In Ecosystems symposium proceedings. David M. Baumgartner, editor. Washington State University, Cooperative Extension Service, Pullman.

Dale, M. 1972. Growth and yield predictions for upland oak stands 10 years after initial thinning. USDA Forest Service Research Paper NE-241, 21 p. Northeastern Forest and Range Experiment Station, Broomall, Pa.

Daniels, R. F., and H. E. Burkhart. 1975. Simulation of individual tree growth and stand development in managed loblolly pine plantations. Publication FWS-5-75, 69 p. Virginia Polytechnic Institute and State University, School of Forestry and Wildlife Resources, Blacksburg.

Daniels, R. F., Harold E. Burkhart, G. D. Spittle, and G. L. Somers. 1979. Methods for modeling individual tree growth and stand development in seeded loblolly pine stands. Publication FSW-1-79, 50 p. Virginia Polytechnic Institute and State University, School of Forestry and Wildlife Resources, Blacksburg.

Davis, Bob. 1972. Economic potential for converting woodland and pasture to cropland. USDA Economic Research Report 459, 24 p. Washington, D.C.

Davis, L. S. 1976. A model for system assessment and data gaps in the 1975 assessment. p. 13-23. In Seminar report from Utah State University on the Resources Planning Act of 1974. 65 p. Logan.

Dell, T. R., D. P. Feduccia, T. E. Campbell, W. F. Mann, Jr., and B. H. Palmer. 1979. Yields of unthinned slash pine plantations on cutover sites in the West Gulf region. USDA Forest Service Research Paper S0-147, 84 p. Southern Forest Experiment Station, New Orleans, La.

Dideriksen, Raymond I., Allen R. Hidlebaugh, and Keith O. Schmude. 1977. Potential cropland study, 1975. Statistical Bulletin 578, 104 p. U.S. Department of Agriculture Soil Conservation Service, Washington, D.C.

Dieraul, T. A., and R. L. Mader. 1965. Pulpwood yields of planted loblolly pine in the Piedmont and Coastal Plain of Virginia. Occasional Report 21, 4 p. Virginia Division of Forestry, Richmond.

Dowdle, Barney. 1962. Investment theory and forest management planning. Yale University, School of Forestry Bulletin 67, 63 p. New Haven, Conn.

Dress, P. E. 1970. A system for the stochastic simulation of even-aged forest stands of pure species composition. Ph.D. dissertation, 267 p. Purdue University. West Lafayette, Ind.

Dudek, A., and A. R. Ek. 1980. A bibliography of worldwide literature on individual tree-based forest growth stand models. Staff Paper Series No. 12, 33 p. University of Minnesota, Department of Forest Resources, St. Paul.

Duerr, William A. 1960. Fundamentals of forestry economics. 579 p. McGraw-Hill, New York, N.Y.

Duerr, William A. 1977. Planning an escape from our forest production-goal muddle, p. 83-96. In Long-range planning in forestry. Frank J. Convery, editor. 227 p. Duke University, School of Forestry, Durham, N.C.

Duerr, William A., Dennis E. Teeguarden, Sam Guttenberg, and Neil B. Christiansen. 1975. Forest Resource Management: Decisionmaking principles and cases. Oregon State University Bookstores, Corvallis.

Dutrow, George F., J. Michael Vasievich, and M. E. Conkin. 1982. Economic opportunities to increase softwood production on private lands. Volume I. 109 p. USDA Forest Service, Area Planning and Development, State and Private Forestry. Washington, D.C.

Edminster, Carleton B. 1978. RMYLD: Computation of yield tables for even-aged and two-storied stands. USDA Forest Service Research Paper RM-199, 26 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Eisenman, Eric, Lee C. Wensel, Edward C. Thor, and Thomas W. Stuart. 1980. Economic data for wildland management in the Western United States: A source guide. USDA Forest Service General Technical Report PSW-42, 125 p. Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif.

Ek, Alan R. 1974. Nonlinear models for stand table projection in northern hardwood stands. Canadian Journal of Forest Research 4:23-27.

Ek, Alan R. 1977. Models for maximizing yield: Optimizing spatial patterns, stocking, species composition and harvest. p. 61-75. *In* Proceedings of workshop: Quantitative ecology: Its application to forest resources management and education. [Dec. 1-3, 1975] University of New Hampshire, Durham.

Ek, Alan R., and J. D. Brodie. 1975. A preliminary analysis of short-rotation aspen management. Canadian Journal of Forest Research 5:245-258.

Ek, Alan R., and Albert Dudek. 1980. Development of individual tree based stand growth simulators: Progress and applications. Staff Paper No. 20, University of Minnesota, Department of Forest Resources, St. Paul.

Ek, Alan R., and Robert A. Monserud. 1974. FOREST: A computer model for the growth and reproduction of mixed species forest stands. College of Agricultural Life Sciences Research Report R2635, 85 p. University of Wisconsin, Madison.

Ek, Alan R., and Robert A. Monserud. 1979. Performance and comparison of stand growth models based on individual tree and diameter-class growth. Canadian Journal of Forest Research 9:231-244.

Ek, Alan R., Dietmar W. Rose, and M. T. Checky. 1980. A brief description of MFPS: A multipurpose forest projection system. Staff Paper No. 16, University of Minnesota, Department of Forest Resources, St. Paul.

Evans, Peter A. 1979. Directory of selected forestry-related bibliographic data bases. USDA Forest Service General Technical Report PSW-34. 42 p. Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif.

Farr, W. A. 1967. Board-foot tree volume tables and equations for white spruce in interior Alaska. USDA Forest Service Research Note PNW-59. 4 p. Pacific Northwest Forest and Range Experiment Station, Portland, Oreg.

Farrar, R. M. 1979a. Status of growth and yield information in the South. Southern Journal of Applied Forestry 3:132-137.

Farrar, Robert M. 1979b. Growth and yield predictions for thinned stands of even-aged natural longleaf pine. USDA Forest Service Research Paper SO-156, 78 p. Southern Forest Experiment Station, New Orleans, La.

Feduccia, D. P., T. R. Dell, W. R. Mann, Jr., T. E. Campbell, and B. H. Palmer. 1979. Yields of unthinned loblolly pine plantations on cutover sites in the West Gulf Region. USDA Forest Service Research Paper SO-148, 88 p. Southern Forest Experiment Station, New Orleans, La.

Field, Richard C. 1978. An overview of modern methods for timber management planning. 21 p. [Paper presented at Southeastern Biometrics Workshop, Roanoke, Va., September 14-15, 1978]. USDA Forest Service, Atlanta, Georga.

Field, Richard C., Peter E. Dress, and James C. Fortson. 1980. Complementary linear and goal programming procedures for timber harvest scheduling. Forest Science 26(1):121-133.

Fight, Roger D., and Enoch F. Bell. 1977. Coping with uncertainty—A conceptual approach for timber management planning. USDA Forest Service General Technical Report PNW-59, 18 p. Pacific Northwest Forest and Range Experiment Station, Portland, Oreg.

Fight, Roger D., and Donald R. Gedney. 1973. The land base for management of young-growth forests in the Douglas-fir region. USDA Forest Service Research Paper PNW-159, 24 p. Pacific Northwest Forest and Range Experiment Station, Portland, Oreg.

Fleming, Frank N. 1980. A cost-effectiveness evaluation of cropland diversion programs in Georgia. M.S. thesis, 60 p. University of Georgia, Athens.

Flick, Warren A., John R. Bowers, and Peter Trenchi, III. 1980. Loblolly pine plantations in southern highlands: Some financial guides. Southern Journal of Applied Forestry 2:107-113.

Flora, Donald F. 1966. Economic guides for a method of precommercial thinning of ponderosa pine in the Northwest. USDA Forest Service Research Paper PNW-31, 10 p. Pacific Northwest Forest and Range Experiment Station, Portland, Oreg.

Forest Industries Council. 1980. Forest productivity report. 66 p. National Forest Products Association. Washington, D.C.

Frayer, Warren E., and Daniel B. Jones. 1970. Effect of estimated inputs on the output of a stand-projection system—A Monte Carlo approach. 8 p. Colorado State University, College of Forestry and Natural Resources, Department of Forest and Wood Sciences Report, Fort Collins.

Fries, J., Harold E. Burkhardt, and T. A. Max. 1978. Growth models for long-term forecasting of timber yields. Publication FWS-1-78, 249 p. Virginia Polytechnic Institute and State University, School of Forestry and Wildlife Resources, Blacksburg.

Gansner, David A., and Owen W. Herrick. 1973. The timber supply potential of intensive management in upland oak forests of Ohio. USDA Forest Service Research Paper NE-271, 8 p. Northeastern Forest Experiment Station, Upper Darby, Pa.

Gardner, W. E., P. Marsh, R. C. Kellison, and D. J. Frederick. 1982. Yields of natural hardwood stands in the southeastern United States. Hardwood Research Cooperative Series No. 1, 57 p. School of Forest Resources, North Carolina State University, Raleigh.

Gedney, Donald R., Carl A. Newport, and Dwight Hair. 1966. Prospective economic developments based on the timber resources of the Pacific Northwest. 174 p. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oreg.

Gedney, Donald R., Daniel D. Oswald, and Roger D. Fight. 1975. Two projections of timber supply in the Pacific Coast States. USDA Forest Service Resource Bulletin PNW-60, 40 p. Pacific Northwest Forest and Range Experiment Station, Portland, Oreg.

Goebel, N. B., and R. D. Shipman. 1969. Volume yields of loblolly pine plantations for a variety of sites in the South Carolina Piedmont. Clemson University Forest Research Series No. 13, 23 p. Clemson, S.C. [Originally published in 1964].

Goebel, N. B., J. R. Warner, and D. H. Von Lear. 1974. Periodic thinnings in loblolly pine stands: Growth, yield, and economic analysis. Series No. 28, 11 p. Clemson University, Department of Forestry Research, Clemson, S.C.

Goldsmith, Lee. 1976. DIADIS: A computer program for simulating growth of white pine by diameter classes. 28 p. New Hampshire Agricultural Experiment Station, University of New Hampshire, Durham.

Goforth, Marcus H., and Thomas J. Mills. 1975. A financial return program for forestry investments—including sensitivity of results to data errors. U.S. Department of Agriculture Handbook 488, 18 p. Washington, D.C.

Goulding, C. J. 1972. Simulation techniques for a stochastic model of the growth of Douglas-fir. Ph.D. thesis, 234 p. University of British Columbia, Forestry Faculty. Vancouver, Canada.

Gregory, G. Robinson. 1955. An analysis of forest production goal methodology. Journal of Forestry 53:237-252.

Gregory, G. Robinson, Dwight Hair, H. R. Josephson et al. 1971. Forecasting in forestry and the timber economy. Folia For Fenn 101:1-49.

Gruschow, G. F., and T. C. Evans. 1959. The relations of cubic volume growth to stand density in young slash pine stands. Forest Science 5:49-55.

Hahn, J. T., D. M. Belcher, M. R. Holdaway, G. J. Brand, and S. R. Shifely. 1979. FREP78: The updated tree growth projection system. p. 211-222. *In* Forest Resource Inventories, Vol. I. W. E. Frayer, editor. Colorado State University, Fort Collins.

Hamilton, David A., Jr. 1978. Specifying precision in natural resource inventories. p. 276-281. *In* Integrated inventories of renewable natural resources: Proceedings of the workshop. H. Gyde Lund, editor. USDA Forest Service General Technical Report RM-55, 482 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Hamilton, David A., Jr., and Bruce M. Edwards. 1976. Modeling the probability of individual tree mortality. USDA Forest Service Research Paper INT-185, 22 p. Intermountain Forest and Range Experiment Station, Ogden, Utah.

Hann, David W. 1980. Development and evaluation of an even- and uneven-aged ponderosa pine/Arizona fescue stand simulator. USDA Forest Service Research Paper INT-267, 95 p. Intermountain Forest and Range Experiment Station, Ogden, Utah.

Hann, David W., and B. Bruce Bare. 1979. Uneven-aged forest management: State-of-the-art (or science)? USDA Forest Service General Technical Report INT-50, 18 p. Intermountain Forest and Range Experiment Station, Ogden, Utah.

Hann, David W., and J. Douglas Brodie. 1980. Even-aged management: Basic managerial questions and available or potential techniques for answering them. USDA Forest Service General Technical Report INT-83, 29 p. Intermountain Forest and Range Experiment Station, Ogden, Utah.

Hann, David W., and Kurt Riitters. 1982. A key to the literature on forest growth and yield in the Pacific Northwest: 1910-1981. Oregon State University Forest Research Laboratory Research Bulletin 39, 77 p. Corvallis.

Hardie, I. W. 1977. Optimal management regimes for loblolly pine plantations in the mid-Atlantic region. Publication No. 906, 107 p. Maryland Agricultural Experiment Station, University of Maryland, Department of Agricultural and Resource Economics, College Park.

Hatch, C. R. 1971. Simulation of an even-aged red pine stand in northern Minnesota. Ph.D. dissertation, 120 p. University of Minnesota, St. Paul.

Heady, Earl O. 1952. Economics of agricultural production and resource use. 850 p. Prentice-Hall, New York, N.Y.

Hegyi F. 1974. A simulation model for managing jack pine stands. p. 74-90. *In* Growth models for tree and stand simulation. J. Fries, editor. Research Note 30, Royal College of Forestry, Department of Forest Yield Research, Stockholm, Sweden.

Hepp, Todd E. 1982. YIELD: Timber yield forecasting and planning tool. Southern Journal of Applied Forestry 6(3):135-140.

Herrick, Owen W., and J. Edwin Morse. 1968. Investment analysis of stand improvement and reforestation opportunites in Appalachian forests. USDA Forest Service Research Paper NE-111, 43 p. Northeastern Forest Experiment Station, Upper Darby, Pa.

Hidlebaugh, Allen R. 1980. Agricultural land data sheet: National Agricultural Lands Study Interim Report 2. U.S. Department of Agriculture, Soil Conservation Service, Washington, D.C. (Chart).

Hilliker, R. L., H. H. Webster, and J. W. Tritch. 1969. Cost relationships for evaluating timber management opportunities in the Lake States. Journal of Forestry 67(3):170-174.

Hoganson, Howard H. 1981. Timber management scheduling under uncertainty. Ph.D. thesis, 150 p. University of Minnesota, College of Forestry, St. Paul.

Holley, D. Lester. 1979. Growing timber as an investment on nonindustrial private lands in the South. 31 p. Southern Forest Landowner Forum. [Atlanta, Ga., July 23-24, 1979].

Holley, D. Lester, Jr., Richard W. Haynes, and H. F. Kaiser, Jr. 1975. An interregional timber model for simulating change in the softwood forest economy. 40 p. Technical Report No. 54, North Carolina State University, Raleigh.

Hough, Franklin B. 1878. Report upon forestry, Volume I. 650 p. U.S. Government Printing Office, Washington, D.C.

Hough, Franklin B. 1880. Report upon forestry, Volume II. 618 p. U.S. Government Printing Office, Washington D.C.

Hoyer, G. E. 1975. Measuring and interpreting Douglas-fir management practices (explanation of a simulation technique, its results and meaning). DNR Report 26. 80 p. Washington State Department of Natural Resources, Olympia.

Huang, Wen-yuan, Stan A. Schraufnagel, and Burton C. English. 1981. Estimation of land availability in the CARD-NRED LP system. Center for Agricultural and Rural Development Working Paper, 35 p. Iowa State University, Ames.

Husch, Bertram, Charles I. Miller, and Thomas W. Beers. 1972. Forest mensuration. Second edition. 410 p. Ronald Press Co., New York, N.Y.

Hyde, William F. 1980. Timber supply, land allocation, and economic efficiency. 214 p. John Hopkins University Press for Resources for the Future, Inc., Baltimore, Md.

Jackson, David H. 1980. The microeconomics of the timber industry. 127 p. Westview Press, Boulder, Colo.

Jackson, David H., and Alan G. McQuillan. 1979. Montana timber supply: A long run model and analysis of alternative approaches. 69 p. Montana Forest and Conservation Experiment Station, University of Montana, Missoula.

Jackson, David H., and Alan G. McQuillan. 1980. A technique for estimating timber value based on tree size, management variables, and market conditions. Forest Science 25(4):620-626.

Jakes, P. J., and W. B. Smith. 1980. Predicted yields from selected cutting prescriptions in northern Minnesota. USDA Forest Service Research Paper NC-188, 29 p. North Central Forest Experiment Station, St. Paul, Minn.

Jensen, H. R., and L. M. Day. 1961. Surveys and studies to estimate farmer's "planned" or "proposed" supply response. p. 177-186. *In* Agricultural supply functions-estimating techniques and interpretations. Earl O. Heady et al., editors. Iowa State Press, Ames.

Johnson, K. Norman, and H. Lynn Schuerman. 1977. Techniques for prescribing optimal timber harvest and investment under different objectives—discussion and synthesis. Forest Science Monograph 18.

Johnson, K. Norman, Daniel B. Jones, and Brian M. Kent. 1980. Forest planning model (FORPLAN) user's guide and operations manual. (Draft). USDA Forest Service, Fort Collins, Colo.

Johnson, K. Norman, H. Lynn Schuerman, and J. H. Beuter. 1975. Oregon timber resource model—a brief introduction. p. 148-163. *In* Systems analysis and forest resource management. J. D. Meadows, B. B. Bare, K. W. Ware, and C. Row, editors. Society of American Foresters, Bethesda, Md.

Joyce, L. A., B. McKinnon, J. G. Hof, and T. W. Hoekstra, 1983. Analysis of multiresource production for national assessments and appraisals. USDA Forest Service General Technical Report RM-101, 20 p. Rocky Mountain Forest and Range Experiment Station. Fort Collins, Colo.

Kao, Chiang, and J. Douglas Brodie. 1979. Determination of optimal thinning entry interval using dynamic programming. Forest Science 25(4):672-674.

Kingsley, Neal P., and Carl E. Mayer. 1972. The extent, composition, and general condition of northern conifer plantations in the northern region. 16 p. Conference on Utilization of Plantation Grown Northern Softwoods, New York State University, College of Environmental Science and Forestry. [Syracuse, N.Y., September 6-7, 1969] Northeastern Forest Experiment Station, Upper Darby, Pa.

Knight, Herbert A. 1973. Land-use changes which affected Georgia's forest land, 1961-1972. USDA Forest Service Research Note SE-189, 4 p. Southeastern Forest Experiment Station, Asheville, N.C.

Knight, Herbert A., and Joe P. McClure. 1974. Opportunities for increasing timber supplies in the Southeast. USDA Forest Service Resource Bulletin SE-28, 16 p. Southeastern Forest Experiment Station, Asheville, N.C.

Koss, W., and B. D. Scott. 1978. Investment guidelines for Douglas-fir. Washington Department of Natural Resources Report 37. 50 p. Olympia.

Kurtz, William B., Ralph J. Alig, and Thomas J. Mills. 1980. Retention and condition of Agricultural Conservation Program conifer plantings. Journal of Forestry 78:273-276.

Larson, Robert W., and Marcus H. Goforth. 1970. TRAS: A computer program for the projection of timber volume. Agricultural Handbook 377, 24 p. U.S. Department of Agriculture, Forest Service, Washington, D.C.

Larson, Robert W., and Marcus H. Goforth. 1974. TRAS: A timber volume projection model. USDA Forest Service Technical Bulletin 1508, 15 p. Washington, D.C.

Leak, William B. 1980. Rapid economic analysis of northern hardwood stand improvement options. USDA Forest Service Research Note NE-296, 6 p. Northeastern Forest Experiment Station, Broomall, Pa.

Ledyard, John, and Leon N. Moses. 1976. Dynamics and land use: The case of forestry. Chap. 9. *In* Public and Urban Economics. 332 p. Ronald E. Grieson, editor. Lexington Books, Lexington, Ky.

Lee, Y. 1967. Stand models for lodgepole pine and limits to their application. Forest Chronicle 43:387-388.

Lemmon, P. E., and F. X. Schumacher. 1962. Volume and diameter growth of ponderosa pine trees as influenced by site index, density, age, and size. Forest Science 8:236-249.

Lemmon, P. E., and F. X. Schumacher. 1963. Theoretical growth and yield of hypothetical ponderosa pine stands under different thinning regimes. Forest Science 9:33-43.

Lenhart, J. D. 1972. Cubic volume yields for unthinned old-field loblolly pine plantations in the Interior West Gulf Coastal Plain. Texas Forestry Paper 14, 46 p. Austin.

Lenhart, J. D., and J. L. Clutter. 1971. Cubic foot yield tables for old-field loblolly pine plantations in the Georgia Piedmont. Georgia Forest Research Council Report 22, Series 3, 13 p. Athens.

Lewis, Bernard J., and Paul V. Ellefson. 1983. Information for timber management and planning: An assessment of availability and adequacy in Minnesota. Minnesota Agricultural Experiment Station Bulletin. (In press).

Lewis, Gordon D., and Daniel E. Chappelle. 1964. Farm woodland management cost and returns in the Southern Piedmont of Virginia. USDA Forest Service Research Paper SE-15, 20 p. Southeastern Forest Experiment Station, Asheville, N.C.

Lin, J. Y. 1974. Stand growth simulation models for Douglas-fir and western hemlock in the northwestern United States. p. 102-118. *In* Growth models for tree and stand simulation. J. Fries, editor. Research Note 30, Royal College of Forestry, Department of Forestry Yield Research, Stockholm, Sweden.

Lohrey, R. E., and R. L. Bailey. 1977. Yield tables and stand structure for unthinned longleaf pine plantations in Louisiana and Texas. USDA Forest Service Research Paper S0-133, 53 p. Southern Forest Experiment Station, New Orleans, La.

Lundgren, Allen L. 1966. Estimating investment returns from growing red pine. USDA Forest Service Research Paper NC-2, 48 p. North Central Forest Experiment Station, St. Paul, Minn.

Lundgren, Allen L., and Emmett F. Thompson. 1972. Uncertainity in forestry investment decisions regarding timber growing. Publication FWS-1-72, 31 p. Virginia Polytechnic Institute and State University, Division of Forestry and Wildlife, Blacksburg.

Lynch, D. W. 1958. Effects of stocking on site measurement and yield of second-growth ponderosa pine in the Inland Empire. USDA Forest Service Research Paper INT-56, 36 p. Intermountain Forest and Range Experiment Station, Ogden, Utah.

Lynch, Thomas B. 1982. Diameter distribution growth and yield models for mixed species forest stands. Ph.D. dissertation. Purdue University, Lafayette, Ind.

Lyon, Kenneth S., and Roger A. Sedjo. 1983. An optimal control theory model to estimate the regional long-term supply of timber. Forest Science (in press).

MacDonald, Purificacion O., Warren E. Frayer, and Jerome K. Clauser. 1979. Documentation, chronology, and future projections of bottomland hardwood habitat loss in the Lower Mississippi Alluvial Plain. Vol. 1: Basic report for the USDI, Fish and Wildlife Service, Division of Ecology Services. 133 p. HRB-Singer, Inc., State College, Pa.

MacKinney, A. L., F. X. Schumacher, and L. E. Chaiken. 1937. Construction of yield tables for non-normal loblolly pine stands. Journal of Agriculture Research 54:531-545.

Manthy, Robert S. 1970. An investment guide for cooperative forest management in Pennsylvania. USDA Forest Service Research Paper NE-156, 59 p. Northeastern Forest Experiment Station, Upper Darby, Pa.

Martin, A. J., and P. E. Sendak. 1973. Operations research in forestry: A bibliography. USDA Forest Service General Technical Report NE-8, 90 p. Northeastern Forest Experiment Station, Upper Darby, Pa.

Martin, George L. 1978. A dynamic network analysis of silvicultural alternatives for red pine. Ph.D. dissertation. University of Wisconsin, Madison.

Martin, George L., and Alan R. Ek. 1981. A dynamic programming analysis of silvicultural alternatives for red pine plantations in Wisconsin. Canadian Journal of Forest Research 11:370-379.

Marty, Robert. 1964. Analyzing uncertain timber investments. USDA Forest Service Research Paper NE-23, 21 p. Northeastern Forest Experiment Station, Upper Darby, Pa.

Marty, Robert. 1969. Some special problems of forecasting timber supplies. Journal of Forestry 67:88-91.

Marty, Robert. 1973. Softwood sawtimber supply and demand projections. Appendix C of Report of the President's Advisory Panel on Timber and the Environment. 541 p. U.S. Government Printing Office, Washington D.C.

Marty, Robert. 1979. Options for calculating allowable timber harvests. Agricultural Experiment Station, Research Report 413. 7 p. Michigan State University, East Lansing.

McArdle, R. E., W. H. Meyer, and D. Bruce. 1961. The yield of Douglas-fir in the Pacific Northwest. Agricultural Technical Bulletin 201, 74 p. United States Department of Agriculture, Washington, D.C.

McCarl, Bruce A., and T. Spreen. 1980. Price endogenous mathematical programming as a tool for sector analysis. American Journal of Agricultural Economics 62(1):87-102.

McCauley, Orris, D., and David A. Marquis. 1972. Investment in precommercial thinning of northern hardwoods. USDA Forest Service Research Paper NE-245, 13 p. Northeastern Forest Experiment Station, Upper Darby, Pa.

McComb, W. H. 1975. Mismanagement by the small landowner: Fact or fiction? Journal of Forestry 73:224-224.

McKillop, William L. 1967. Supply and demand for forest products, an econometric study. Hilgardia 38:1-132. University of California Agriculture Experiment Station, Berkeley.

Meadows, D. 1980. The unavoidable a priori. p. 23-57. *In* Elements of the systems dynamics methods. J. Randers, editor. 320 p. MIT Press, Cambridge, Mass.

Meister, A. D., and K. J. Nicol. 1975. A documentation of the national water assessment model of regional agricultural production, land and water use, and environmental interaction. Center for Agricultural and Rural Development, Miscellaneous Report, 220 p. Iowa State University, Ames.

Meyer, A. H. 1952. Structure, growth, and drain in balanced uneven-aged forests. Journal of Forestry 50:85-92

Meyer, W. H. 1938. Yield of even-aged stands of ponderosa pine. Agricultural Technical Bulletin 630, 59 p. USDA Forest Service, Pacific Northwest Forest Experiment Station, Portland, Oreg.

Mills, Thomas J. 1976. Cost effectiveness of 1974 Forest Incentives Program. USDA Forest Service Research Paper RM-175, 23 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Mills, Thomas J., and Ralph J. Alig. 1979. Projections of timber supplies for the United States: 1976-2030. *In* Timber Supply: Issues and options. [San Francisco, Calif., October 2-4, 1979] 218 p. Forest Products Research Society, Madison, Wis.

Mills, Thomas J., and Daria Cain. 1978. Timber yield and financial return performance of the 1974 Forest Incentives Program. USDA Forest Service Research Paper RM-204, 56 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Mills, Thomas J., D. B. Shinkle, and Gregory L. Cox. 1983. Direct cost of silvicultural treatments on National Forests, 1975-78. USDA Forest Research Paper. Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif. (In press).

Mitchell, Kenneth J. 1969. Simulation of the growth of even-aged stands of white spruce. School of Forestry Bulletin No. 75, 48 p. Yale University, New Haven, Conn.

Mitchell, Kenneth J. 1975. Dynamics and simulated yield of Douglas-fir. Forest Science Monograph No. 17. 39 p.

Moak, James E. 1982. Forest practice cost trends in the South. Southern Journal of Applied Forestry 6(3):130-132.

Moak, James E., and James M. Kucera. 1975. Current costs and cost trends for forestry practices in the South. Forest Farmer 34(5):75-82.

Moak, James E., James M. Kucera, and William F. Watson. 1977. Current costs and cost trends for forestry practices in the South. Forest Farmer 36(5):16-21.

Moak, James E., W. F. Watson, and P. Van Deusen. 1980. Costs and cost trends for forestry practices in the South. Forest Farmer 39(5):58-66.

Moeur, Melinda, and Alan R. Ek. 1981. Plot, stand, and cover-type aggregation effects on projections with an individual tree based stand growth model. Canadian Journal of Forest Research 11:309-315.

Monserud, Robert A. 1978. Implementation of Prognosis model for forest stand development for combined assessment of silvicultural and Douglas-fir tussock moth (DFTM) control activities. 90 p. USDA Forest Service Pacific Northwest Forest and Range Experiment Station, Portland, Oreg.

Monserud, Robert A., and N. L. Crookston. 1982. A user's guide to the combined stand Prognosis and Douglas-fir tussock moth outbreak model. USDA Forest Service General Technical Report INT-127, 49 p. Intermountain Forest and Range Experiment Station, Ogden, Utah.

Montgomery, Albert A., Vernon L. Robinson, and James D. Strange. 1975. An economic model of Georgia's long run timber market. Georgia Forest Research Council Report 34, 21 p. Athens.

Montgomery, Albert A., Vernon L. Robinson, and James D. Strange. 1976. Impacts of land-use competition and other constraints on Georgia's future timber supply. Georgia Forest Research Council Report 36, 25 p. Athens.

Moser, John W. 1974. A system of equations for the components of forest growth. p. 260-288. *In* Growth models for tree and stand simulation. J. Fries, editor. Research Note 30, Royal College of Forestry, Department of Forestry Yield Research, Stockholm, Sweden.

Moser, John W., Carl H. Tubbs, and Rodney D. Jacobs. 1979. Evaluation of a growth projection system for uneven-aged northern hardwoods. Journal of Forestry 77(7):421-423.

Munro, D. D. 1974. Forest growth models—A prognosis. p. 7-21. *In* Growth models for tree and stand simulation. J. Fries, editor. Research Note 30, Royal College of Forestry, Department of Forestry Yield Research, Stockholm, Sweden.

Murphy, Paul A. 1982. Sawtimber growth and yield for natural, even-aged stands of shortleaf pine in the West Gulf. USDA Forest Service, Research Paper SO-181, 13 p. Southern Forest Experiment Station, New Orleans, La.

Murphy Paul A., and H. S. Sternitzke. 1979. Growth and yield estimation for loblolly pine in the West Gulf. USDA Forest Service Research Paper SO-154, 8 p. Southern Forest Experiment Station, New Orleans, La.

Myers, Clifford A. 1971. Field and computer procedures for managed stand yield tables. USDA Forest Service Research Paper RM-79, 15 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Myers, Clifford A., Carleton B. Edminster, and Frank G. Hawksworth. 1976. SWYLDZ: Yield tables for even-aged and two-storied stands of southwestern ponderosa pine, including effects of dwarf mistletoe. USDA Forest Service Research Paper RM-163, 25 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Navon, Daniel I. 1971. Timber RAM: A long range planning method for commercial timber lands under multiple-use management. USDA Forest Service Research Paper PSW-70, 22 p. Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif.

Navon, Daniel I., and S. Weintraub. 1982. Operations research in forestry: State of the art. Paper presented at joint meeting of TMIS-ORSA, April 18-21, 1982. 24 p. Detroit, Mich.

Nelson, T. C., J. L. Clutter, and L. E. Chaiken. 1961a. Yield of Virginia pine. USDA Forest Service Station Paper 124, 11 p. Southeastern Forest Experiment Station, Asheville, N.C.

Nelson, T. C., T. Lotti, E. V. Brender, and K. B. Trousdell. 1961b. Merchantable cubic foot volume growth in natural loblolly pine stands. USDA Forest Service Station Paper 127, 12 p. Southeastern Forest Experiment Station, Asheville, N.C.

Newnham, R. M. 1964. The development of a stand model for Douglas-fir. Ph.D. dissertation, 201 p. University of British Columbia, Vancouver, Canada.

Newnham R. M., and J. H. G. Smith. 1964. Development and testing of stand models for Douglas-fir and lodgepole pine. Forest Chronicle 40:494-502.

Nodine, Stephen K., and Allen Marsinko. 1979. Impacts of the Soil Bank's Conservation Reserve Program on forestry in South Carolina. Forest Research Series No. 32, 39 p. Clemson University, Department of Forestry, Clemson, S.C.

Oliver, W. O., and R. F. Powers. 1978. Growth models for ponderosa pine. *In* Yield of unthinned plantations in Northern California. USDA Forest Service Research Paper PSW-133. 9 p. Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif.

Oswald, Daniel D. 1978. Prospects for sawtimber output in California's North Coast, 1975-2000. USDA Forest Service Resource Bulletin PNW-74, 20 p. Pacific Northwest Forest and Range Experiment Station, Portland, Oreg.

Payandeh, Bijan. 1973. Plonski's yield tables formulated. Publication No. 1318. 14 p. Canadian Forestry Service, Department of the Environment, Ottawa.

Rahm, C. M. 1981. Timber supply analysis and baseline simulations. Forest Policy Project Module III—A Final Report, 125 p. Washington State University. Boeing Computer Services Company, The Consulting Division, Renton.

Randall, Robert M. 1977. Financial consequences of commercial thinning regimes in young-growth Douglas-fir. USDA Forest Service Research Note PNW-293, 8 p. Pacific Northwest Forest and Range Experiment Station, Portland, Oreg.

Reynolds, Marion, R., Harold E. Burkhart, and Richard F. Daniels. 1981. Procedures for statistical validation of stochastic simulations models. Forest Science 27(2):349-364.

Riitters, Kurt, J. Douglas Brodie, and David W. Hann. 1982. Dynamic programming for optimization of timber production and grazing in ponderosa pine. Forest Science 28(3):517-526.

Risbrudt, Christopher D., and Paul V. Ellefson. 1983. An economic evaluation of the 1979 Forestry Incentives Program. University of Minnesota, Agricultural Experiment Station Bulletin Number 550, 55 p. Minneapolis.

Robinson, Vernon L. 1974. An econometric model of softwood lumber and stumpage markets, 1949-1967. Forest Science 20:171-179.

Robinson, Vernon L., Albert A. Montgomery, and James D. Strange. 1978. GASPLY: A computer model for Georgia's future forest. 21 p. Georgia Forest Research Council Report No. 36A. Athens.

Rose, Dietmar W., Hans M. Gregersen, Alan R. Ek, and Howard Hoganson. 1981. Planning with minimum data and technology. p. 188-197. *In* Proceedings of the International Union of Forestry Research Organization (IUFRO) symposium on forest management planning: Present practice and future decisions. [Blacksburg, Va., August 18-20, 1980] Publication FWS-1-81, 22 p. Virginia Polytechnic Institute and State University, School of Forestry and Wildlife Resources, Blacksburg.

Row, Clark. 1973. Probabilities of financial returns from Southern pine timber growing. Ph.D. dissertation, 428 p. Tulane University, New Orleans, La.

Row, Clark. 1977. Balancing supplies and demands. p. 83-158. *In* Research in forest economics and forest policy. Marion F. Clawson, editor. Research Paper R-3, 555 p. Resources for the Future, Washington, D.C.

Row, Clark. 1978. Economies of tract size in timber growing. Journal of Forestry 76:576-582.

Sassaman, R. W., E. Holt, and K. Bergsvik. 1972. User's manual for a computer program for Simulating Intensively Managed Allowable Cut. USDA Forest Service General Technical Report PNW-1, 50 p. Pacific Northwest Forest and Range Experiment Station, Portland, Oreg.

Schlaegel, B. E. 1971. Growth and yield of quaking aspen in North Central Minnesota. USDA Forest Service Research Paper NC-58, 11 p. North Central Forest Experiment Station, St. Paul, Minn.

Schmidt, James, and Philip L. Tedder. 1980. TREES: Timber resource economic estimation system—Volume II, mathematical analysis and policy guide. Forest Research Laboratory Bulletin 316, 71 p. Oregon State University, Corvallis.

Schnur, G. L. 1937. Yield, stand, and volume tables for even-aged upland oak forests. USDA Forest Service Technical Bulletin 560, 87 p. U.S. Department of Agriculture, Forest Service, Allegheny Forest Experiment Station, Philadelphia, Pa.

Schreuder, Gerard F. 1968. Optimal forest investment decisions through dynamic programming. Yale University, School of Forestry Bulletin 72, 70 p. New Haven, Conn.

Schreuder, Hans, T., W. L. Hafley, and F. A. Bennett. 1979. Yield prediction for unthinned natural slash pine stands. Forest Science 25:25-30.

Schuler, Albert T., H. H. Webster, and J. C. Meadows. 1977. Goal programming in forest management. Journal of Forestry 75(6):320-324.

Schumacher, F. X., and T. S. Coile. 1960. Growth and yields of natural stands of the southern pines. 115 p. T. S. Coile, Inc., Durham, N.C.

Shulstad, Robert N., and Ralph D. May. 1980. Conversion of noncropland to cropland: The prospects, alternatives, and implications. American Journal of Agricultural Economics 62:1077-1083.

Sizemore, William. 1973. Improving the productivity of nonindustrial private woodlands. Appendix I. *In* Report of the President's Advisory Panel on Timber and the Environment. 541 p. U.S. Government Printing Office, Washington, D.C.

Smalley, G. W., and Robert L. Bailey. 1974a. Yield tables and stand structure for loblolly pine plantations in Tennessee, Alabama, and Georgia highlands. USDA Forest Service Research Paper SO-96, 81 p. Southern Forest Experiment Station, New Orleans, La.

Smalley, G. W., and Robert L. Bailey. 1974b. Yield tables and stand structure for shortleaf pine plantations in Tennessee, Alabama, and Georgia highlands. USDA Forest Service Research Paper SO-97, 57 p. Southern Forest Experiment Station, New Orleans, La.

Smith, H. D., W. L. Hafley, D. L. Holley, and R. C. Kellison. 1975. Yields of mixed hardwood stands occurring naturally on a variety of sites in the southern United States. School of Forest Resources Technical Report 55. 32 p. North Carolina State University, Raleigh.

Smith, W. B., and G. K. Raile. 1979. FREP: Application of the tree growth projection system for inventory. p. 223-230. *In* Forest Resource Inventories. Vol. I. W. E. Frayer, editor. Colorado State University, Fort Collins.

Solomon, Dale S. 1977a. Status of growth and yield information for northern forest types. p. 251-260. *In* Proceedings of the symposium on intensive culture of northern forest types. USDA Forest Service General Technical Report NE-29, 356 p. Northeastern Forest Experiment Station, Upper Darby, Pa.

Solomon, Dale S. 1977b. A growth model of natural and silviculturally treated stands of even-aged northern hardwoods. USDA Forest Service General Technical Report NE-36, 30 p. Northeastern Forest Experiment Station, Upper Darby, Pa.

Somberg, S. I., L. D. Eads, and J. G. Yoho. 1963. What it costs to practice forestry in the South. Forest Farmer 22(13):6-8, 15-17.

Staebler, George R. 1955. Gross yield and mortality tables for fully stocked stands of young growth Douglas-fir. USDA Forest Service Research Paper PNW-14, 20 p. Pacific Northwest Forest and Range Experiment Station, Portland, Oreg.

Stage, Albert R. 1973. Prognosis model for stand development. USDA Forest Service Research Paper INT-137, 32 p. Intermountain Forest and Range Experiment Station, Ogden, Utah.

Stage, Albert R. 1979. Stand prognosis model—The central link in a decision support system for forest managers. Proceedings of the Society of American Foresters 1978:256-257.

Stage, Albert R., Richard K. Babcock, and William R. Wykoff. 1980. Stand-oriented inventory and growth projection methods improve harvest scheduling on Bitterroot National Forest. Journal of Forestry 78:265-267, 278.

Stoddard, Charles H. 1961. The small private forest in the United States. 177 p. Resources for the Future, Washington, D.C.

Stone, Robert N. 1970. A comparison of woodland owner intent with woodland practice in Michigan's Upper Peninsula. Ph.D. dissertation, 114 p. University of Minnesota, St. Paul.

Sullivan, A. D., and J. L. Clutter. 1972. A simultaneous growth and yield model for loblolly pine. Forest Science 18:76-86.

Sunda, Henry J., and Gerald L. Lowry. 1975. Regeneration costs in loblolly pine management. Journal of Forestry 74(5):406-409.

Tedder, Philip L., James S. Schmidt, and Jonna Gourley. 1980. TREES: Timber resource economic estimation system, Vol. I. Forest management and harvest scheduling, a user's guide. Research Bulletin 31a, 81 p. Oregon State University, Forest Research Laboratory, Corvallis.

Tedder, Philip L. 1983. The Timber Resource Inventory Model's (TRIM) integration with the Timber Assessment Market Model p. 171-178. *In* Proceedings of the IIASA, North American conference on forest sector models. [Williamsburg, Va. December 2-4, 1981]. Washington, D.C.

Teeguarden, Dennis E. 1969. Economic criteria and calculated risk in reforestation investment decisions. Journal of Forestry 67(1):24-31.

Teeguarden, Dennis E. 1977. Information resources for research in forest economics and policy. p. 383-432. *In* Research in forest economics and forest policy. Marion F. Clawson, editor. Research Paper R-3, 555 p. Resources for the Future, Washington, D.C.

Tennessee Valley Authority (TVA), Division of Forestry Development. 1962. A report on 85,700 forest plantations in the Tennessee Valley. (8 p. Norris, Tenn. Unnumbered publication).

Thompson, Emmett F. 1968. The theory of decision under uncertainity and possible applications in forest management. Forest Science 14(2):156-163.

Trimble, Judy L., and Carole R. Shriner. 1981. Inventory of United States forest growth models. Report to the International Energy Agency, Forestry Energy System Analysis Working Group. 133 p. Oak Ridge National Laboratory, Oak Ridge, Tenn.

USDA Forest Service. 1920. Timber depletion, lumber prices, lumber exports, and concentration of timber ownership. 71 p. Report on Senate Resolution 311, 66th Congress, 2nd session, Government Printing Office, Washington, D.C. [The Capper Report].

USDA Forest Service. 1933. A national plan for American forestry. 2 vol., 1,677 p. Senate Document 12, 73rd Congress, 1st session, Government Printing Office, Washington, D.C. [The Copeland Report].

USDA Forest Service. 1948. Forests and national prosperity. USDA Miscellaneous Publication 668, 99 p. Government Printing Office, Washington, D.C. [The Reappraisal Report].

USDA Forest Service. 1958. Timber resources for America's future. USDA Forest Resource Report 14, 713 p. Government Printing Office, Washington, D.C.

USDA Forest Service. 1965. Timber trends in the United States. Forest Resource Report 17, 235 p. Government Printing Office, Washington, D.C.

USDA Forest Service. 1969. Douglas-fir supply study: Alternative programs for increasing timber supplies from National Forest lands. USDA Forest Service (Unnumbered publication) 53 p. Pacific Northwest Forest and Range Experiment Station, Portland, Oreg.

USDA Forest Service. 1973. The outlook for timber in the United States. USDA Forest Service Forest Resource Report 20, 376 p. Washington, D.C.

USDA Forest Service. 1976a. The Nation's renewable resources—an assessment, 1975. USDA Forest Service Forest Resource Report 21, 243 p. Government Printing Office, Washington, D.C.

USDA Forest Service. 1976b. Timber harvest scheduling issues study. 292 p. plus appendixes. Washington, D.C.

USDA Forest Service. 1976c. Volume, yield, and stand tables for second-growth southern pines. USDA Miscellaneous Publication 50, 202 p. Washington, D.C.

USDA Forest Service. 1979. A generalized forest growth projection system applied to the Lake States region. USDA Forest Service General Technical Report NC-49, 96 p. North Central Forest Experiment Station, St. Paul, Minn.

USDA Forest Service. 1981. U.S. timber production, trade, consumption, and price statistics: 1950-80. Miscellaneous Publication 1408, 81 p. Washington, D.C.

USDA Forest Service. 1982. An analysis of the timber situation in the United States, 1952-2030. Forest Resource Report No. 23, 499 p. Washington, D.C.

USDC Bureau of the Census. 1977. 1974 Census of Agriculture. Georgia State and County data. Vol. 1, Part 10. Athens.

U.S. President's Advisory Panel on Timber and the Environment. 1973. Report. 541 p. Government Printing Office, Washington, D.C.

Utz, Keith A., and Daniel H. Sims. 1981. Investment analysis of upland oak stands. USDA Forest Service, Forestry Report SA-FR-12, 44 p. Southeastern Area, State, and Private Forestry, Atlanta, Georgia.

Vaux, Henry J. 1954. Economics of young-growth sugar pine resources. Bulletin Number 78. 56 p. University of California, Division of Agricultural Sciences, Berkeley.

Vaux, Henry J. 1970. Public timber supply alternatives in the Douglas-fir region. Hill Family Foundation Series. 37 p. Oregon State University, School of Forestry, Corvallis.

Vaux, Henry J. 1973. How much land do we need for growing timber? Journal of Forestry 71:399-403.

Vaux, Henry J., and John A. Zivnuska. 1952. Forest production goals: A critical analysis. Land Economics 28(4):318-327.

Voelker, A. H. 1975. Some pitfalls of land-use modeling. Oak Ridge National Laboratory, Regional and Urban Studies Department, Oak Ridge, Tenn.

Von Thunen, J. H. 1966. The isolated state. 304 p. Peter Hall, editor. Pergamon Press, London.

Walker, John L. 1971. An economic model for optimizing the rate of timber harvesting. Ph.D. dissertation, 117 p. University of Washington, Seattle.

Wall, Brian R. 1981. Trends in commercial timberland area in the United States by state and ownership, 1952-77, with projections to 2030. USDA Forest Service General Technical Report WO-31, 26 p. Washington, D.C.

Ware, Glen O., and Jerome L. Clutter. 1971. A mathematical programming system for management of industrial forests. Forest Science 17:428-445.

Warrack, G. C. 1959. Forecast of yield in relation to thinning regimes in Douglas-fir. British Columbia Forestry Service Technical Publication T51, 56 p. Vancouver, Canada.

Weaver, G. H., and C. A. Osterhaus. 1976. Economic analysis of planting costs in loblolly pine management. Journal of Forestry 75:217-219.

Webster, Henry H. 1960. Timber management opportunities in Pennsylvania. USDA Forest Service, Northeastern Forest Experiment Station, Station Paper 137, 37 p. Upper Darby, Pa.

White, Fred C., and Frank N. Fleming. 1980. An analysis of competing agricultural land uses. Southern Journal of Agricultural Economics 12(4):99-103.

Wikstrom, J. H., and J. R. Alley. 1967. Cost control in timber growing on the National Forests of the Northern Region. USDA Forest Service Research Paper INT-42., 37 p. Intermountain Forest and Range Experiment Station, Ogden, Utah.

Wiley, K. N., and M. D. Murray. 1974. Ten year growth and yield of Douglas-fir following stocking control. Weyerhauser Company Forest Paper 14. Olympia, Wash.

Williston, Hamlin L. 1972. The question of adequate stocking. Tree Planters Notes 23(1):9-10.

Williston, Hamlin L. 1975. Selected bibliography on growth and yield of the four major southern pines. 27 p. USDA Forest Service, Southeastern Area, State and Private Forestry, Atlanta, Ga.

Williston, Hamlin L., and T. R. Dell. 1974. Growth of pine plantations in north Mississippi. USDA Forest Service Research Paper SO-94, 15 p. Southern Forest Experiment Station, New Orleans, La.

Worthington, N. P., F. A. Johnson, G. R. Staebler, and W. J. Lloyd. 1960. Normal yield tables for red alder. USDA Forest Service Research Paper PNW-36, 3 p. Pacific Northwest Forest and Range Experiment Station, Portland, Oreg.

Yoho, James G. 1961. What it costs to practice forestry in the South. Forest Farmer 21(2):6, 7, 8, 19.

Yoho, James G., G. F. Dutrow, and J. E. Moak. 1969. What it costs to practice forestry. Forest Farmer 28(11):20-24, 26, 28, 30, 31.

Zilberman, David. 1982. The use and potential of optimal control models in agricultural models. Western Journal of Agricultural Economics 7(2):395-405.

Appendix A.—The date, primary analytical approach, and scope for major aggregate timber supply studies in the United States

Study	Year	Analytical approach	Scope
USDA Forest Service (Capper Report)	1920	Growth-drain ratio analysis	U.S.
USDA Forest Service (Copeland Report)	1933	Growth-drain ratio analysis	U.S.
USDA Forest Service (Reappraisal)	1948	Growth-drain ratio analysis	U.S.
USDA Forest Service (Timber Resources Review)	1958	Growth-drain ratio analysis	U.S.
USDA Forest Service (Timber Trends)	1965	Growth-drain ratio analysis	U.S.
Gedney et al. (PNW Economic Base Study)	1966	Stand table projection	Pacific Northwest, Inland Empire
USDA Forest Service (Douglas-Fir Supply Study)	1969	Investment analysis and even-flow modeling	National Forests in Douglas-fir region
Vaux	1970	Investment analysis and even-flow modeling	Douglas-fir region
U.S. President's Advisory Panel on Timber and the Environment	1973	TRAS stand table projection and supply/demand "gap" analysis	U.S.
USDA Forest Service (Outlook)	1973	TRAS stand table projection and supply/demand "gap" analysis	U.S.
Gedney et al.	1975	TRAS stand table projection	Pacific Coast States
Clawson and Hyde	1976	Yield-table projection with investment analysis	Coastal Pacific Northwest
USDA Forest Service (Assessment)	1976a	TRAS stand table projection and supply/demand "gap" analysis	U.S.
USDA Forest Service (Timber Harvest Scheduling Issues Study)	1976b	Investment analysis and even-flow modeling, with price projections	National Forests
Rahm	1981	TREES inventory projection, with economic simulation of timber harvests utilizing a downward sloping, regional demand	Washington, Oregon, Idaho
USDA Forest Service (Analysis of the Timber Situation)	1982	TAMM economic equilibrium modeling	U.S.
Brooks	1983b	Yield table projection, with investment functions and linkage to the TAMM model	Private lands in the South

Appendix B.—Selected recent studies of growth and yield modeling identified by principal species and region

Author	Year	Principal species	Geographic area
		Whole stand models	
Adams and Ek	1974, 1975	Northern hardwoods	Lake States
Alexander et al.	1975	Engelmann spruce	Colorado, Wyoming
Alig et al.	1982	U.S. species	U.S.
Alimi and Barrett	1977	Mixed conifer hardwood	Northeast
Barnes	1955	Slash pine	Florida
Beck and Della-Bianca	1970, 1972	Yellow poplar	Southern Appalachians
Bennett et al.	1959	Slash pine	Southeast
Bennett	1970a, 1970b	Slash pine	Southeast
Bennett and Clutter	1968	Slash pine	Southeast
Brodie and Rose	1975	Jack pine	Wisconsin
Bruce et al.	1977	Douglas-fir	Pacific Northwest
Buckman	1962	Red pine	Lake States
Buongiorno and Michie	1980	North Central hardwoods	North Central States
Burkhart et al.	1972a	Loblolly pine	Southeast
Burkhart et al.	1972b	Loblolly pine	Southeast
Burkhart and Strub	1974	Loblolly pine	Southeast
Cao et al.	1982	Loblolly pine	Southeast
Chambers and Wilson	1972	Douglas-fir	Pacific Northwest
Chambers and Wilson	1978	Western hemlock	Pacific Northwest
Clutter	1963	Loblolly pine	Southeast
Clutter and Allison	1974	Monterrey pine	New Zealand
Coile and Schumacher	1964	Loblolly and and slash pine	South
Curtis	1967	Coastal Douglas-fir	Coastal Pacific Northwest
Curtis et al.	1981	Coastal Douglas-fir	Coastal Pacific Northwest
Dahms	1964, 1975	Lodgepole pine	Oregon
Dale	1972	Mixed oaks	Iowa, Missouri, Kentucky, Ohio
Dell et al.	1979	Slash pine	South
Dieraul and Mader	1965	Loblolly pine	Southeast
Edminster	1978	Ponderosa pine, lodgepole pine, spruce-fir	Rocky Mountains
Ek	1974	Northern hardwoods	Lake States
Ek and Brodie	1975	Aspen	Lake States

Appendix B.—Selected recent studies of growth and yield modeling identified by principal species and region (continued)

Author	Year	Principal species	Geographic area
Farr	1967	White spruce	Interior of Alaska
Farrar	1979	Longleaf pine	South
Fedducia et al.	1979	Loblolly pine	South
Gardner et al.	1982	Mixed hardwoods	South
Goebel and Shipman	1969	Loblolly pine	South Carolina
Goebel et al.	1974	Loblolly pine	South Carolina
Gruschow and Evans	1959	Slash pine	Southeast
Hann	1980	Ponderosa pine	Southwest
Hoyer	1975	Douglas-fir	Pacific Northwest (Washington)
Lenhart	1972	Loblolly pine	Texas
Lenhart and Clutter	1971	Loblolly pine	Georgia
Lohrey and Bailey	1977	Longleaf pine	Louisiana and Texas
Lynch	1958	Ponderosa pine	Northeast Washington, Idaho, West Montana
Lynch	1982	Mixed species: aspen-white pine	Lake States
MacKinney et al.	1937	Loblolly pine	Southeast
McArdle et al.	1961	Coastal Douglas-fir	Western Oregon, Washington
Meyer	1938	Ponderosa pine	West
Moser et al.	1979	Mixed hardwoods	Lake States
Murphy	1982	Shortleaf pine	South (West Gulf)
Murphy and Sternitzke	1979	Loblolly pine	South (West Gulf)
Myers	1971	Ponderosa pine	Rocky Mountains
Myers et al.	1976	Ponderosa pine	Southwest
Nelson et al.	1961a	Virginia pine	Southeast
Nelson et al.	1961b	Loblolly pine	Southeast
Payandeh	1973	Northern species	Southeastern Canada
Schlaegel	1971	Aspen	North Central States
Schnur	1937	Oak-hickory	East
Schreuder et al.	1979	Slash pine	South
Schumacher and Coile	1960	Southern pines	Southeast
Smalley and Bailey	1974a	Loblolly pine	Southeast
Smalley and Bailey	1974b	Shortleaf pine	Southeast
Smith et al.	1975	Mixed hardwoods	South

Appendix B.—Selected recent studies of growth and yield modeling identified by principal species and region (continued)

Author	Year	Principal species	Geographic area
Solomon	1977a, 1977b	Northern hardwoods	New England
Staebler	1955	Coastal Douglas-fir	Western Oregon, Washington
Sullivan and Clutter	1972	Loblolly pine	South
USDA Forest Service	1976c	Southern pines	South
Warrack	1959	Douglas-fir	British Columbia
Wiley and Murray	1974	Coastal Douglas-fir	Pacific Northwest
Worthington et al.	1960	Red alder	Pacific Northwest
	Individual-tree distance-independent models		
Botkin et al.	1972	Northeast mixed forest	Northeast
Ek et al.	1980	Pure or mixed species stands	Lake States
Goulding	1972	Douglas-fir	British Columbia
Lemmon and Schumacher	1962, 1963	Ponderosa pine	Rocky Mountain Region
Martin	1978	Red pine	Wisconsin
Oliver and Powers	1978	Ponderosa pine	California
Stage	1973, 1979	Ponderosa pine, Douglas-fir, lodgepole pine, mixed western species	Northern Rocky Mountains, Pacific Northwest
USDA Forest Service	1979	Lake States species	Lake States
	Individual-tree distance-dependent models		
Arney	1974	Douglas-fir	Pacific Northwest
Daniels and Burkhart	1975	Loblolly pine	Southeast
Daniels et al.	1979	Loblolly pine	South
Dress	1970	Even-aged pure species stands	Not geographically limited
Ek and Monserud	1974	Northern hardwoods	Lake States
Goldsmith	1976	Eastern white pine	Northeast
Hatch	1971	Red pine	Lake States
Hegyi	1974	Jack pine	Ontario
Lee	1967	Lodgepole pine	British Columbia, Alberta
Lin	1974	Douglas-fir, western hemlock	Pacific Northwest
Mitchell	1969	White spruce	New England
Mitchell	1975	Douglas-fir	Pacific Northwest
Newnham	1964	Douglas-fir	British Columbia
Newnham and Smith	1964	Douglas-fir, lodgepole pine	British Columbia

Appendix C.—Selected recent timber investment and cost studies by region of the United States and principal species

Author	Year	Principal species	Geographic area
		Timber investment studies	
Adams and Ek	1974	Northern hardwoods	Lake States
Adams and Ek	1975	Northern hardwoods	Lake States
Amidon and Akin	1968	Loblolly pine	South
Anderson	1968	Southern pine	Georgia
Anderson and Guttenberg	1971	Oak-pine conversion to loblolly and slash pine	South
Beuter and Handy	1974	Douglas-fir	Western Oregon
Broderick et al.	1982	Loblolly pine	Virginia
Brodie et al.	1978	Douglas-fir	Pacific Northwest
Brodie and Kao	1979	Douglas-fir	Pacific Northwest
Callahan and Smith	1974	Black walnut	Midwest
Chappelle and Nelson	1964	Loblolly pine	South
Clawson and Hyde	1976	Douglas-fir	Coastal Pacific Northwest
Ek and Brodie	1975	Aspen	Lake States
Fight and Gedney	1973	Douglas-fir	Pacific Northwest
Flick et al.	1980	Loblolly pine	South (highlands)
Flora	1966	Ponderosa pine	Pacific Northwest
Forest Industries Council	1980	U.S. species	U.S.
Gansner and Herrick	1973	Upland oak	Ohio
Gedney et al.	1975	Pacific Northwest softwoods	Pacific Coast States
Hardie	1977	Loblolly pine	Mid-Atlantic
Herrick and Morse	1968	Appalachian forests	Virginia, W. Virginia
Hyde	1980	Douglas-fir	Pacific Northwest
Jackson and McQuillan	1979	Northern Rocky Mountain species	Montana
Knight and McClure	1974	Southern pine	Southeast
Koss and Scott	1978	Douglas-fir	Pacific Northwest
Leak	1980	Northern hardwoods	New England
Lewis and Chappelle	1964	Southern species	Virginia
Lundgren	1966	Red pine	Lake States
Manthy	1970	Softwoods/hardwoods	Pennsylvania
Marty	1973	Softwoods	U.S.
McCauley and Marquis	1972	Northern hardwoods	North
Mills	1976	U.S. species	U.S.

Appendix C.—Selected recent timber investment and cost studies by region of the United States and principal species (continued)

Author	Year	Principal species	Geographic area
		Timber investment studies—continued	
Randall	1977	Douglas-fir	Pacific Northwest
Row	1973	Southern pine	South
Row	1978	U.S. species	U.S.
Utz and Sims	1981	Upland oak	East
Vaux	1954	Sugar pine	California
Vaux	1973	California conifers	California
Webster	1960	White pine, Norway spruce	Pennsylvania
		Cost studies	
Conkin	1971	Northern species	North
Cox	1980	U.S. species	U.S.
Hilliker et al.	1969	Lake States species	Lake States
Mills et al.	1982	U.S. species	U.S.
Moak and Kucera	1975	Southern species	South
Moak et al.	1977	Southern species	South
Moak et al.	1980	Southern species	South
Moak	1982	Southern species	South
Somberg et al.	1963	Southern species	South
Sunda and Lowry	1975	Loblolly pine	South
Weaver and Osterhaus	1976	Loblolly pine	South
Wikstrom and Alley	1967	Lodgepole pine	Montana, Idaho
Yoho	1961	Southern species	South
Yoho et al.	1969	Southern species	South

Appendix D.—Studies of retention and condition of timber investments on private lands

Author	Year	Program	Geographic area	Practice type	Performance measure
Alig et al.	1980	Soil Bank	South	Pine plantations	Retention and condition
Kingsley and Mayer	1972	Mixture of cost share and private	North	Conifer plantations	Condition
Kurtz et al.	1980	Agricultural Conservation Program (ACP)	East	Conifer plantations	Retention and condition
Mills and Cain	1978	Forestry Incentives Program (FIP)	U.S.	Hardwood and conifer practices	Timber yield and financial return
Nodine and Marsinko	1979	Soil Bank	South Carolina	Pine plantations	Retention and condition
Risbrudt and Ellefson	1983	Forestry Incentives Program (FIP)	U.S.	Hardwood and conifer practices	Timber yield and financial return
Stone	1970	-----	Michigan	-----	-----
Tennessee Valley Authority (TVA)	1962	Soil Bank, ACP, CCC, private	Tennessee Valley	Pine and hardwood plantations	Retention and condition
Williston	1972	Yazoo-Little Tallahatchie Flood Prevention project	Northern Mississippi	Pine plantations	Retention and condition
Williston and Dell	1974	Civilian Conservation Corps (CCC)	Northern Mississippi	Pine plantations	Retention and condition

GLOSSARY

DIAMETER CLASS: A classification of trees based on tree diameter (including bark) measured at breast height (4-5 feet above the ground). D.b.h. is the common abbreviation for diameter at breast height, and 2-inch intervals or diameter classes are commonly used.

DIRECT GROWTH AND YIELD MODEL: Models in which the underlying sampling information is used directly as a basis for projecting forest development for a particular area or stand.

EMPIRICAL YIELD TABLES: Tabular presentation of the yield of stands or trees for average stand conditions under existing management practices.

ENDOGENOUS VARIABLES: Variables whose values are simultaneously determined by the model and which the model is designed to explain.

ENGINEERING FUNCTION: A function (or model) based on parameters estimated according to technical or engineering efficiency considerations.

EXOGENOUS VARIABLES: Variables originating from external causes, whose values are determined outside the model but influence the model.

HARVEST FLOWS: Annual or periodic estimates of timber that will be cut over time on a particular aggregate.

HARVEST SCHEDULING: A method for estimating a planned sequence of cutting and reforestation activities that are scheduled according to a prescribed norm, including the acres and volume harvested through each activity.

INDIRECT GROWTH AND YIELD MODEL: Models that are applied to subject stands or areas larger in nature than those from which the underlying sample growth and yield data was obtained, with two different sets of data used for model construction and application.

INGROWTH: Number of trees that grow into a particular timber-size class during a specified interval of time.

INVENTORY: Quantity of stumpage existing at a certain point in time for a specified geographical area (this term is also often used to refer to the activity of collecting data on the stock of timber).

LONG RUN or LONG TERM: A period of time in which all factors involved in the production process are considered variable.

MARGINAL ANALYSIS: Economic optimization principle that contribution to total revenue of an additional unit produced (i.e., marginal revenue) should equal the contribution to total cost of producing an additional unit (i.e., marginal cost).

NORMAL YIELD TABLES: Tabular presentation of the yield of "fully stocked," undisturbed natural stands by site-index and stand-age categories.

NORMATIVE MODELING APPROACH: Analytical framework designed to show what ought to be, given certain conditions and assumptions (i.e., prescriptive).

POSITIVE MODELING APPROACH: Analytical framework designed to describe things as they do exist or are likely to exist based on empirical or historical evidence (i.e., descriptive or predictive).

PRECOMMERCIAL THINNING: Removal of some unmerchantable trees from a forest stand to promote enhanced growth of the remaining trees.

PRODUCTION FUNCTION: Technical relationship between inputs and outputs in a production process; it is often expressed as an equation, as when the quantity of stumpage (output) is defined as a function of the relevant inputs (e.g., land).

RESOURCES PLANNING ACT (RPA): The Forest and Rangeland Resources Planning Act of 1974, which requires integrated planning between levels of state and federal agencies, including assessments at each level that culminate in a national assessment of the renewable resources.

SAWTIMBER: Live trees that are above a certain d.b.h. and contain merchantable lengths; for example, softwood sawtimber trees in the Pacific Northwest must be 11.0 inches in d.b.h. or larger and contain at least a 12-foot sawlog or two noncontiguous 8-foot sawlogs.

SENSITIVITY ANALYSIS: Procedure by which values for coefficients or variables are changed and the impact on a target value or solution observed. This technique is often used, for example, to see if an optimal solution is highly sensitive to the values used for variables that are not known with certainty.

SHORT RUN: Period of time in which one or more factors involved in the production process is considered fixed.

STOCK: Entire amount of standing timber existing at a particular point in time; it is also termed physical supply or inventory.

STOCKING: Degree of occupancy of land by trees, measured by basal area and/or number of trees by size or age and spacing, compared to a standard.

TIMBER DEMAND: Schedule of the quantities of stumpage that consumers are willing to purchase at different prices in a market specified as to time and place. Demand for stumpage is "derived" from the demand for other wood products such as lumber and plywood.

TIMBER SUPPLY: Schedule of the quantities of stumpage that producers are willing to offer for sale at different prices in a specific market area in a given time period.

TIMBER SUPPLY ANALYSIS: Examination and investigation of a timber supply complex, its elements, and their relations, in the context of a functional relationship between quantity of stumpage that would be supplied (or produced) and price.

☆ U.S. Government Printing Office 1984 - 778-121/9176 Reg. 8

Alig, Ralph J. 1984. Aggregate timber supply analysis. USDA Forest Service General Technical Report RM-106, 49 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Timber supply analysis techniques for broad geographical levels are summarized by land allocation, timber growth and yield, short-term harvest flows, and long-term timber investment modeling components. Representative techniques of these major analytical components are summarized in tabular form for supply regions. Aspects of uncertainty and aggregation in timber supply analyses are also discussed.

Keywords: Timber supply analyses, regional timber supply, long-term timber supply projections

Alig, Ralph J. 1984. Aggregate timber supply analysis. USDA Forest Service General Technical Report RM-106, 49 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Timber supply analysis techniques for broad geographical levels are summarized by land allocation, timber growth and yield, short-term harvest flows, and long-term timber investment modeling components. Representative techniques of these major analytical components are summarized in tabular form for supply regions. Aspects of uncertainty and aggregation in timber supply analyses are also discussed.

Keywords: Timber supply analyses, regional timber supply, long-term timber supply projections

Alig, Ralph J. 1984. Aggregate timber supply analysis. USDA Forest Service General Technical Report RM-106, 49 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Timber supply analysis techniques for broad geographical levels are summarized by land allocation, timber growth and yield, short-term harvest flows, and long-term timber investment modeling components. Representative techniques of these major analytical components are summarized in tabular form for supply regions. Aspects of uncertainty and aggregation in timber supply analyses are also discussed.

Keywords: Timber supply analyses, regional timber supply, long-term timber supply projections

Alig, Ralph J. 1984. Aggregate timber supply analysis. USDA Forest Service General Technical Report RM-106, 49 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Timber supply analysis techniques for broad geographical levels are summarized by land allocation, timber growth and yield, short-term harvest flows, and long-term timber investment modeling components. Representative techniques of these major analytical components are summarized in tabular form for supply regions. Aspects of uncertainty and aggregation in timber supply analyses are also discussed.

Keywords: Timber supply analyses, regional timber supply, long-term timber supply projections

U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

Rocky Mountains

Southwest

Great Plains

The Rocky Mountain Station is one of eight regional experiment stations, plus the Forest Products Laboratory and the Washington Office Staff, that make up the Forest Service research organization.

RESEARCH FOCUS

Research programs at the Rocky Mountain Station are coordinated with area universities and with other institutions. Many studies are conducted on a cooperative basis to accelerate solutions to problems involving range, water, wildlife and fish habitat, human and community development, timber, recreation, protection, and multiresource evaluation.

RESEARCH LOCATIONS

Research Work Units of the Rocky Mountain Station are operated in cooperation with universities in the following cities:

Albuquerque, New Mexico
Flagstaff, Arizona
Fort Collins, Colorado*
Laramie, Wyoming
Lincoln, Nebraska
Rapid City, South Dakota
Tempe, Arizona

*Station Headquarters: 240 W. Prospect St., Fort Collins, CO 80526